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Energy Utilization by Wet Scrubbers

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ENERGY UTILIZATION BY WET SCRUBBERS

by

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ABSTRACT

An experimental pilot-plant investigation was made of the comparative performance of particulate scrubbers that draw contacting power for gas/liquid contacting from the gas stream and from the liquid stream. Three synthetic polydisperse test aerosols were used; these had similar size distributions but different mass-median particle diameters of 1.05, 0.68, and 0.42 μm, respectively. The different contactors were compared on the basis of collection efficiencies obtained at given levels of contacting power, using the performance of an orifice contactor as a reference level.

A series contactor consisting of staggered, multiple orifices in series gave essentially the same performance as the single-orifice contactor at the higher contacting power levels but tended to give poorer performance at the lower power levels. This behavior was accentuated as the aerosol particle size decreased.

Five different pressure spray nozzles were tested, as was a sixth spray nozzle in combination with a single orifice. All these contactor configurations gave poorer performance than did the reference orifice scrubber at the same total contacting power. However, the deviation of the efficiency from the reference level proved to be a function of the fraction of the total contacting power that was derived from the liquid stream. The relative deviation of the spray scrubber efficiency from the reference level increased as the aerosol particle size decreased.

All the spray contactors but one gave very similar performances at comparable conditions despite radical differences in spray nozzle designs and spray configurations.

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ABBREVIATIONS AND NOMENCLATURE

ABBREVIATIONS

atm -- atmospheres (pressure)
cm -- centimeters
cm WC -- centimeters of water (pressure)
ft -- feet
g -- grams
gal -- gallons
hp -- horsepower
kWh -- kilowatt hours
m -- meters
mg -- milligrams
min -- minutes
mm -- millimeters
N -- normality (of solution)
nm -- nanometers
SEM -- scanning electron microscope
std -- standard (state of gas)
μg -- micrograms
μm -- micrometers

NOMENCLATURE

f -- fraction, P_L/P_T
F_E -- effective friction loss, cm WC
N_t -- number of transfer units, dimensionless
P_f -- liquid feed pressure, atm gauge
Δp -- pressure drop, cm WC
P_G -- gas-phase contacting power, kWh/1000 m^3
P_L -- liquid-phase contacting power, kWh/1000 m^3
P_T -- total contacting power, kWh/1000 m^3

α -- coefficient of P_T in equation $N_t = \alpha P_T^{\gamma}$, $[\mathrm{kWh}/1000\ \mathrm{m}^3]^{-\gamma}$

γ -- exponent of P_T in equation $N_t = \alpha P_T^{\gamma}$, dimensionless

η -- fractional collection efficiency, dimensionless

$1 - \eta$ -- fractional penetration, dimensionless

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SECTION 1

INTRODUCTION

GENERAL

Wet scrubbers are used widely for removal of particulate matter, including submicrometer particles, from waste gases. The scrubbers in use are able to attain high collection efficiencies if sufficient energy is applied to the gas/liquid contacting process. However, the energy required to attain a given efficiency increases with decrease in particle size and becomes particularly high for particles smaller than one micrometer.

There are three basic ways in which the necessary energy can be introduced into the gas/liquid contacting process: from the gas stream, from the liquid stream, or through a mechanical rotor. There are almost innumerable variations in the details of methods and equipment used to introduce the energy by these paths. However, it has not been known what method of introducing the energy produces optimum results, or even whether there is a clear and definite optimum method. A considerable body of data has indicated that the collection efficiency of a scrubber is determined primarily by the power per unit of volumetric gas flow rate ("contacting power") consumed in the gas/liquid contacting process, and is not much affected by the method of introducing the power or by the configuration of the device in which contacting takes place. The equivalence of most scrubbers that take contacting power from the gas stream in the form of pressure drop is quite well established by results of specific studies and by a body of general experience. Additional information has also indicated that contacting power taken from the liquid stream is probably equivalent to that taken from the gas stream; this indication has been modified by the results of the present investigation. A small amount of data suggests that contacting power from a mechanically driven rotor may also be equivalent, but that question remains unresolved.

Obviously, it is extremely important for scrubber selection and design to know whether there actually are significant differences in the contacting power/efficiency relationships corresponding to the different ways of introducing the contacting power. Even if different scrubbers showed no significant differences in inherent collection efficiency at a given contacting power, specific scrubber configurations may offer distinct practical advantages for particular applications.

OBJECTIVES

The broad objectives of this investigation were:

(1) To determine the effect of the method of introducing contacting power on the collection efficiency of particulate scrubbers.

(2) To determine the effect of aerosol particle size on the contacting power/efficiency relationship for particles in the low-micrometer and submicrometer size range.

The specific tasks of the scope of work included the following:

(1) Review and assessment of the published literature and available unpublished information pertaining to the effects of energy consumption and different methods of energy application on the collection of particles by scrubbers.

(2) A bench-scale experimental study of fine-particle collection by representative types of scrubbers that derive contacting power from (a) the gas stream, (b) the liquid stream, and (c) a mechanical rotor. Three test aerosols were to be used, all having particle diameters of less than 3 micrometers and at least one having a particle diameter of less than 0.8 micrometer. The experiments were to include study of series scrubbing through use of multiple contactors or scrubbers in series.

(3) For all the scrubbers studied:

   (a) Development of quantitative relationships between the energy supplied to the scrubber and the particle collection efficiency.

   (b) Explanation, to the extent possible, of any differences that might appear among the contacting power/collection efficiency relationships for different types of scrubbers.

   (c) Identification, so far as possible, of the mechanisms by which the energy supplied to the scrubber is used to collect particles.

   (d) Identification, so far as possible, of the energy-consuming mechanisms.

(4) Recommendation of existing designs, design modifications, operating practices, or other factors in scrubber performance that might be found to optimize particle collection efficiency in existing scrubbers, especially for fine particles.

(5) Development of specific recommendations, together with cost and time estimates, for a program to research, develop, and demonstrate scrubbers that will make optimum use of energy and liquid for particle collection.

SECTION 2

SUMMARY AND CONCLUSIONS

The investigation of the energy consumption and collection efficiency of scrubbers was accomplished by comparing the performances of different devices on the same synthetic test aerosols. All tests were conducted with ambient air as the gas and water at ambient temperature as the scrubbing liquid. The performance of an orifice scrubber, a unit of conventional design that had been studied earlier, was determined and served as the baseline for comparison with other devices. The critical element in the experimental program was ensuring that the test aerosols remained consistent. Producing test aerosols of tolerable consistency, determining that the consistency was maintained in each test run, and determining the particle sizes and size distributions consumed by far the greatest part of the project effort. By comparison, the remainder of the experimental techniques used in scrubber testing were relatively simple.

The aerosols were produced from sprays of ammonium fluorescein solutions. Upon drying, the droplets left solid, spherical particles of sizes determined by the original droplet sizes and by the concentration of ammonium fluorescein in the solution. The residual solid was indicated to be the monoammonium salt, which has a very low solubility in water and is nonhygroscopic. Very small quantities of the aerosol could be determined precisely by fluorimetric analysis.

All the available practical methods for spray generation produced polydisperse particles. Initially, an effort was made to use an SRI-developed pneumatic atomizer, but this unit failed to give consistent results. The effort was switched to a second SRI-developed aerosol generator based on an ultrasonic nebulizer with numerous modifications designed to enhance the stability. This unit still showed variations in the aerosol produced, but in general the consistency was tolerable. Monitoring the consistency of the aerosol remained a problem, but was accomplished by sampling the aerosol entering the scrubber with a "miniscrubber."

The miniscrubber consisted of four Greenburg-Smith impingers in series, followed by a final filter. The unit was always operated at the same gas pressure drop. By analysis of the aerosol collected in each impinger and on the final filter, the collection efficiency of each stage could be calculated. The efficiencies were expressed as the number of transfer units, and the cumulative number of transfer units at each collection stage was plotted as a function of the cumulative gas pressure drop. The resulting curve, which was termed the "aerosol signature" or "signature curve," was characteristic of a given aerosol, and changes in the curve denoted a change in the aerosol. If the degree of change was excessive, the results of the test could be excluded.

The character and particle-size span of an aerosol were determined from scanning electron microscope studies of the aerosol collected on a Nuclepore membrane filter. The mass particle-size distributions and mass-median diameters were determined from measurements with an Andersen cascade impactor with greased impact plates.

Three test aerosols were used. These were designated as D, E, and G, and had indicated mass-median particle diameters of 1.05, 0.68, and 0.42 μm, respectively. The standard deviations of the distributions were about 1.6-1.7.

The gas/liquid contactors investigated are described in summary in Table 1. The orifice contactor was generally representative of conventional orifice or venturi contactors. It had been extensively investigated with a different aerosol in an earlier study, and was taken as the reference unit. Performance curves (curves of number of transfer units versus contacting power on a log-log scale) were determined for the orifice scrubber for each of the three aerosols. All three aerosols proved to have two-branched performance curves.

The multiple-orifice series contactor consisted of four staggered, eccentric orifices in series. This unit gave the same performance as the single-orifice scrubber over the upper part of the contacting power range, but lower efficiencies over the lower part of the range. The magnitude of the deviation and the contacting power level below which the deviation appeared both increased as the aerosol particle size decreased. It is not known whether this behavior is characteristic of series contactors in general, but there was no indication that series contactors should be expected to give performance superior to that of a single-stage contactor.

With the spray contactors and the combination spray-orifice contactor, some friction loss (and gas pressure drop) always attended flow of the air through the scrubber, so that the total contacting power always included gas-phase as well as liquid-phase components.

The SS5 and SO configurations could be operated as ejectors, with all the draft for air flow through the scrubber being supplied by the water jets from the nozzles.

Except when the relative amount of liquid-phase contacting power was very low, the efficiencies of the spray scrubbers and the spray-orifice scrubber were definitely lower than those of the orifice scrubber. The deviation from the orifice scrubber performance curve proved to be correlated by a simple parameter $\underline{f}$, the ratio of the liquid-phase contacting power to the total contacting power. The deviation increased with increase in the value of $\underline{f}$. However, for given values of $\underline{f}$, spray

TABLE 1. GAS/LIQUID CONTACTORS

Contactor	Test code	Gas line diameter (cm)	Orifice diameter (cm)	Spray nozzle type	Nozzle position in gas line	Spray orientation	Spray angle
Orifice	OS	5.84	2.54 3.81				
Multiple orifices in series	MOS	5.84	3.36[a]				
Spray	SS1	5.84		Perforated tube (multiple perforations)	Concentric	Radial, crossflow	0°
Spray	SS2	5.84		Flat spray	Sidewall	Crossflow	95°
Spray	SS3	5.84		Full cone, wide angle	Concentric	Cocurrent	100°
Spray	SS4	5.84		Deflected, hollow cone	Concentric	Radial, crossflow	180°
Spray	SS5	5.84		Full cone, injector type	Concentric	Cocurrent	30°
Spray and orifice	SO	5.84	2.54 3.81	Full cone	Concentric	Cocurrent	60°

[a] Diameter of circle having same area as semicircular orifice.

scrubber configurations SS1, 2, and 3 gave almost identical performances despite radical differences in nozzle design and orientation and in spray characteristics. Configurations SS5 and SO gave only slightly better performance than SS1, 2, and 3. Only the SS4 configuration gave an efficiency markedly different (lower) from the general level of the other spray contactors.

When configurations SS5 and SO were operated as ejector scrubbers, the performance at a given contacting power agreed well with that of other spray configurations at high values of $\underline{f}$.

Because of the large effort that had to be devoted to aerosol development, measurement, and monitoring, the time and funds available for the project were not sufficient to permit an investigation of mechanical rotor gas/liquid contactors.

Some major conclusions from the investigation are:

(1) No indication was found of the existence of a narrowly defined optimum way of applying contacting power in particulate scrubbing. Further evidence was added to earlier observations that for a given aerosol there is a level of performance that cannot be exceeded with a given gas-phase contacting power; certain scrubber configurations or operating modes may give poorer performance than the "norm," but not better performance.

(2) Liquid-phase contacting power was found to be broadly less effective than gas-phase contacting power. However, it is not clear whether the apparent inferiority of the liquid-phase contacting power is real, or whether the discrepancy may be partly or wholly due to the difficulty of estimating the quantity of liquid-phase contacting power actually consumed in gas/liquid contacting, which cannot be measured directly.

(3) The relative contribution of liquid-phase contacting power to collection efficiency was not increased by closely combining the action of the spray with that of a gas-phase turbulence promoter, as in the spray-orifice combination contactor.

(4) Although the various spray-type gas/liquid contactors presumably yielded sprays of radically different characters, these differences produced no evident substantial effects on collection efficiency (except possibly in one case) that were independent of the contacting power applied.

(5) The energy consumed in scrubbing is dissipated in fluid friction and turbulence and is the same whether or not particles are present in the gas phase. The energy dissipation is associated with conditions that lead to particle collection, but the collection process does not involve application of energy directly to the particles.

(6) The relationships observed between scrubber contacting power and collection efficiency do not appear currently to be either predictable or explicable from first principles.

SECTION 3

RECOMMENDATIONS

Since the maximum attainable level of particulate scrubber collection efficiency is evidently determined essentially by the contacting power level, no recommendations can be offered for optimizing the performance of either existing or potential new designs. However, since certain scrubber configurations or operating modes have been found to deliver less than the maximum level of performance, it is highly desirable to avoid using such configurations unless they have other characteristics favorable for specific applications that will outweigh their deficiencies in contacting power/efficiency ratio.

The comparative performance of mechanical rotor scrubbers should also be determined. Although there is currently no reason to expect that the mechanical scrubbers will give performance significantly superior to that of venturi or orifice scrubbers at the same contacting power, they might have practical advantages for certain applications. For example, in an application requiring very high contacting power, the use of a mechanical contactor will avoid the necessity of moving the gas through very large pressure differentials using high-pressure blowers.

The type of experimental approach used in the present investigation, bench-scale comparative testing of basic devices with standardized aerosols over wide ranges of conditions, is a practical one that should be applied more widely. It is essentially a simple technique, provided that a consistent aerosol is available.

SECTION 4

BACKGROUND

Although some observers had previously noted that high collection efficiency in particulate scrubbers was generally associated with high power consumption, it was the work of Lapple and Kamack[1] that first showed that, for a given aerosol, a functional relationship exists between the collection efficiency and the gas pressure drop of scrubbers in which the energy consumed is derived from the gas stream. Equally striking was the observation that different designs of gas/liquid contactors show only modest differences in collection efficiency when operated at the same gas pressure drop. Lapple and Kamack suggested that power input from spray nozzles and mechanically driven rotors might also correlate with scrubber efficiency. Additional evidence for the relationship of scrubber efficiency and pressure drop was obtained from proprietary studies at Stanford Research Institute.[2] Still further support was obtained by Semrau et al.[3] in field studies of pilot plant scrubbers; this work also showed considerable support for the suggestion that power input from spray nozzles might be equivalent to that from gas pressure drop.

The concept of "contacting power" was extended and refined in later publications by Semrau[4,5] (see Appendix A). Correlations of published data from various laboratory and field studies gave additional indications that contacting power from spray nozzles and mechanical rotors might be equivalent to that from the gas stream. Unfortunately, no comparable data taken under carefully controlled conditions have been available to resolve firmly the questions concerning the relative effectiveness of gas-phase, liquid-phase, and mechanical contacting power.

A variety of studies by other investigators has generally supported the equivalence of gas-phase contacting power in different designs of gas/liquid contactors, though still other workers have reported substantial deviations (see Appendix A). Although claims of greatly superior performance are still sometimes made for certain devices, based on supposed novelties of scrubber design or operation, none of these claims have so far been sustained when subjected to critical experimental testing. In a recent study with an orifice scrubber with a synthetic ammonium fluorescein aerosol, Semrau and Witham[6,7] found the collection efficiency to be a function only of contacting power, not independently affected by orifice size, gas velocity through the orifice, or liquid-to-gas ratio. These results supported earlier findings made with much more restricted ranges for the variables.

Since 1963, basic studies of scrubbers have largely been concerned with efforts to develop theoretical models of scrubber operation from first principles. The most elaborate of these studies have been devoted to the venturi scrubber; among the better known models that have been developed are those of Calvert,[8-10] Boll,[11] and Behie and Beeckmans.[12,13] All these models are based on collection of particles of discrete sizes. Calvert has also modified his models to express the scrubber collection efficiencies in terms of the gas pressure drops. However, Calvert's equations contain a factor that absorbs errors and approximations in the derivation of the models, and this factor had to be evaluated from experimental data.

Unfortunately, there are very few experimental data that could be used to evaluate the factor in the Calvert equations or to test the theoretical models of Calvert or other workers. Some investigators have noted substantial deviations between the predicted scrubber performance and that indicated by available experimental data.[11,13] Attempts at experimental verification have commonly covered only narrow ranges of operating variables. Testing of the models requires use of monodisperse aerosols or of measurements of the collection efficiency for particles of discrete sizes if polydisperse aerosols are used. The production of monodisperse aerosols is difficult to accomplish and control, and a narrow size distribution rather than true monodispersivity is the best that can be obtained in practice. Measurements of particle-size distribution at the inlet and outlet of a scrubber are also difficult and, in some circumstances at least, of questionable reliability. The sheer laboriousness of the latter technique, in particular, usually limits the number of determinations and the ranges of scrubber operating variables that can be reasonably investigated.

The experimental approach used in the present study, comparative testing of scrubber units with standardized aerosols, is a relatively simple technique, although producing and monitoring a "standardized aerosol" is by no means simple, as is demonstrated below. Ideally, the test aerosol should be monodisperse, to permit evaluation of the scrubber performance in terms of absolute particle size. But even if production of a monodisperse aerosol is impractical, it is possible to make reliable comparisons of the actual behavior of different scrubbers. Essentially, the scheme is to reduce all determinations to those quantities that can be measured with relative simplicity and confidence. As far as possible, it is necessary to avoid making the comparison of devices dependent on a chain of measurements that may accumulate errors or uncertainties.

The experimental problem lies primarily in generation of the aerosol, which must be stable, reproducible, and readily measurable in quantity if not in particle size. In addition, the generation technique must be rapid and relatively simple to permit large numbers of tests. It is far more critical that the aerosol particle-size characteristics remain constant than that they be known in detail on an absolute basis. Nevertheless, it is important to know as much as practical about the particle-size characteristics of the aerosol. In particular, the aerosol should be dispersed as discrete particles to the greatest possible extent. In practice, this requires use of low aerosol concentrations to limit coagulation, which in turn requires choice of an aerosol material that is readily determinable in small quantities.

The nature of an aerosol material and the available technique for generation are interrelated. Attaining given desired aerosol properties commonly requires sacrificing others, so that any choice represents a compromise.

SECTION 5

EXPERIMENTAL METHODS AND EQUIPMENT

PILOT-PLANT SCRUBBER

The small pilot-plant experimental scrubber system is portrayed schematically in Figure 1. The same unit was previously used in a project entitled "Wet Scrubber Liquid Utilization" (EPA Contract No. 68-02-1079), which was actually concerned with condensation and evaporation effects in scrubbing and was reported by Semrau and Witham.[8] The components of the original system that were not used in the present study have been omitted from Figure 1. This system was designed to accommodate inlet gas flows of up to about 4200 liters/min (150 ft^3/min) at ambient temperature, and with gas pressure drops across the scrubber of up to 300 cm WC (120 inches WC). The scrubber itself consisted of the contactor section followed by a cyclone entrainment separator. The contactor section consisted of a vertical section of line in which the chosen gas/liquid contactor was mounted and through which the gas flowed downward. The gas and water leaving the contactor section passed through a mitre elbow before flowing horizontally into the cyclone separator.

When an orifice gas/liquid contactor was used, the orifice plate was mounted in a horizontal plane between flanges in the vertical line. Interchangeable orifice plates were used to vary the diameter of the contacting orifice. The scrubbing water was introduced through a single tap in the wall of the inlet line, 2 pipe diameters above the orifice plate. The orifice scrubber design thus followed on a small scale the general configuration currently being used for most commercial scrubbers of the orifice or modified venturi types.

Air was drawn through the system by a rotary positive-displacement blower of the Roots type. The main air flow through the system was drawn directly from the room and metered before entering the scrubber. The air flow through the system was controlled by bleeding air from the room directly to the inlet of the positive-displacement blower. The air bypass intake was fitted with a filter-silencer and the blower with a discharge silencer. However, the main air stream entering the system was not filtered; since the test aerosol was measured by a specific fluorimetric method, the presence of atmospheric dust in the room air did not interfere with the determination of scrubber efficiency.

The contactor section was made from 2-1/2-inch stainless steel tubing (5.84 cm inside diameter). The cyclone separator, which was actually larger than necessary to handle the gas flows used, was 45.7 cm

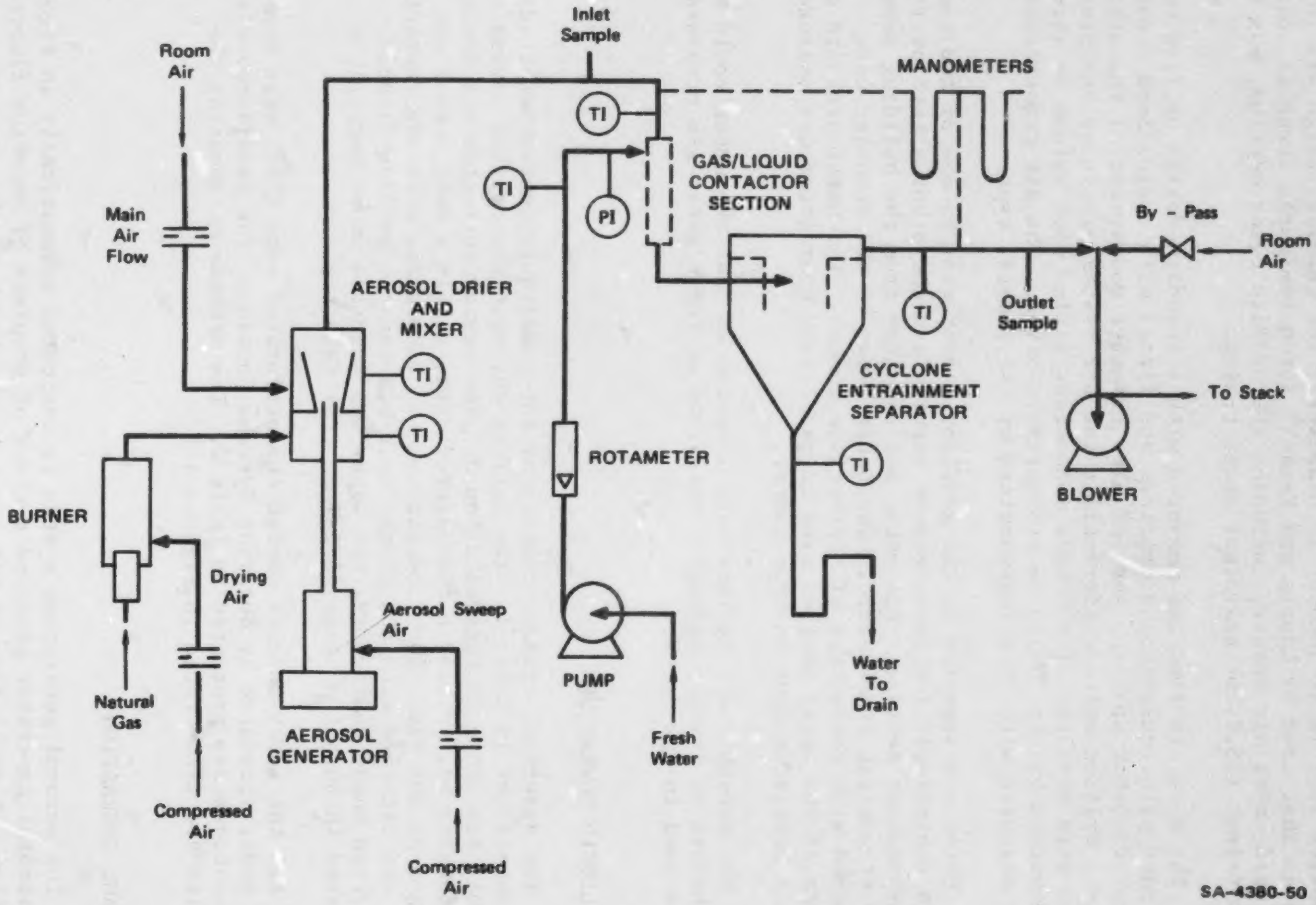

Inlet Sample
Room Air
MANOMETERS
TI
GAS/LIQUID CONTACTOR SECTION
TI
PI
Main Air Flow
By - Pass
Room Air
AEROSOL DRIER AND MIXER
TI
Outlet Sample
TI
CYCLONE ENTRAINMENT SEPARATOR
To Stack
TI
ROTAMETER
TI
BURNER
BLOWER
Drying Air
Aerosol Sweep Air
Natural Gas
PUMP
Water To Drain
AEROSOL GENERATOR
Fresh Water
Compressed Air
Compressed Air
SA-4380-50

FIGURE 1 FLOWSHEET OF EXPERIMENTAL SCRUBBER SYSTEM

(18 inches) in diameter, with an inlet 7.6 cm (3 inches) in diameter and an outlet 10.2 cm (4 inches) in diameter. The general design was the same as that used by Lapple and Kamack[1] for a semiworks scrubber unit. The main inlet air header, including the orifice meter section, was made from 6-inch (15.2-cm) stainless steel tubing.

The main air flow was measured with a standard-design orifice meter equipped with square-edged orifices and fitted with radius taps located 1 pipe diameter upstream and 1/2 pipe diameter downstream of the orifice plate. Orifice meter differentials and air system pressures and pressure drops were measured with U-tube manometers filled with xylene or mercury, as demanded by the ranges of pressures involved. The air temperatures were measured with dial thermometers of the bimetal type.

Water was supplied to the gas/liquid contactor by one of two pumps, one a centrifugal for low-pressure service and the other a turbine for high-pressure service. The water was supplied from the building supply line at ambient temperature. The water flows to the scrubber were measured with rotameters of appropriate ranges. The water pressure upstream of the spray nozzles used as gas/liquid contactors was measured with a precision Bourdon-type gauge.

The scrubber and cyclone were elevated so that the water could be discharged by gravity through a seal loop at the highest gas pressure drops used in the tests.

GAS/LIQUID CONTACTORS

The essential characteristics of the gas/liquid contactors studied are summarized in Table 1. The orifice and multiple-orifice series contactors are shown in Figures 2 and 3. The series contactor was formed by mounting half-discs in a staggered array within a tube, which was flanged at one end. The tube was mounted concentric with the contactor line and retained with the flange held between the orifice flanges. With both these contactors, the water was injected under negligible pressure through the large (1/2-inch IPS) feed tap.

All the spray nozzles except the perforated tube (SS1) were commercial models produced by Spraying Systems Company. The manufacturer's designations are presented in Table 2. The methods of mounting the nozzles are illustrated in Figures 4-9.

AEROSOL GENERATION

The aerosol generation system is indicated schematically in Figure 1. The aerosol generator produced a cloud of droplets of ammonium fluorescein solution. A small flow of air swept the mist out of the generator and straight upward through a section of 1-inch IPS pipe. The 1-inch pipe extended to the lower end of a conical diffuser section, which was located

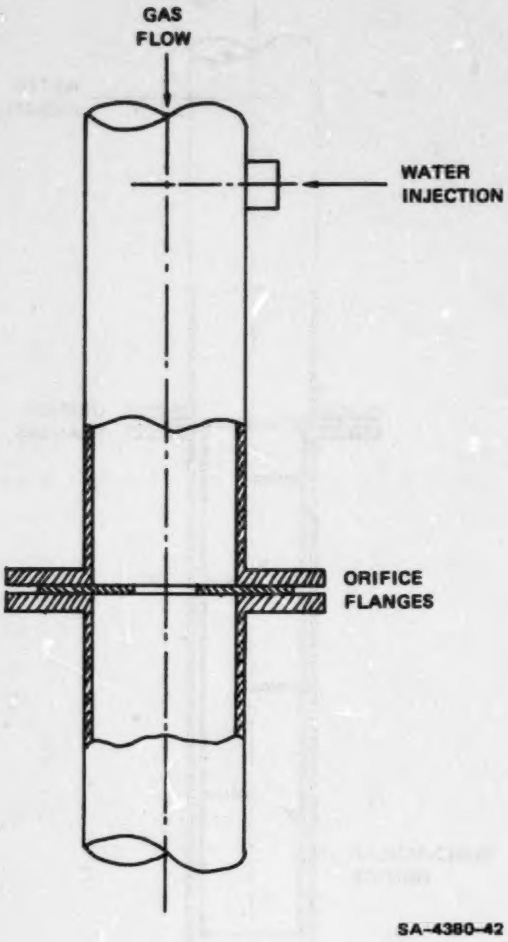
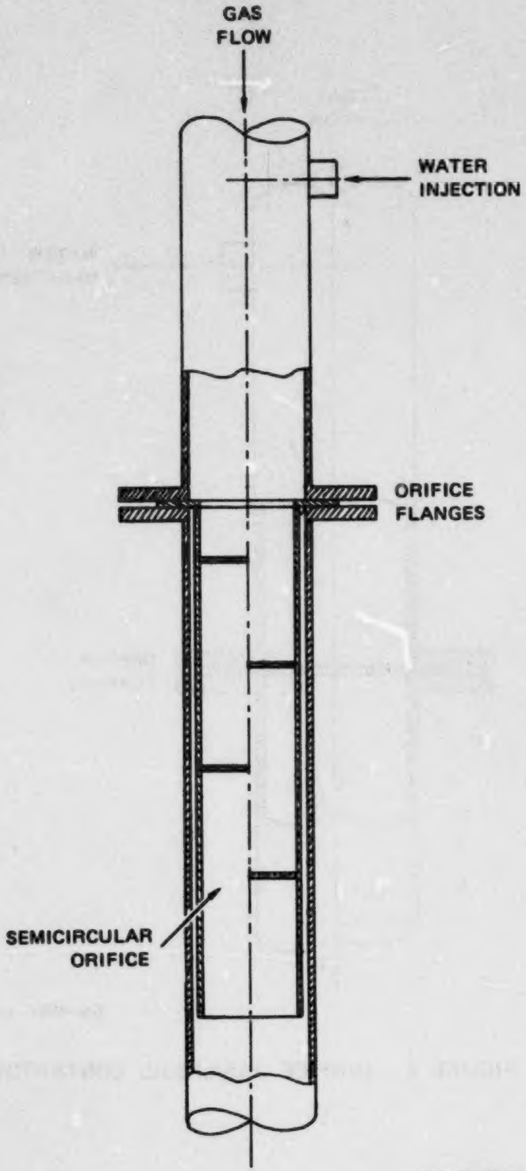

GAS
FLOW
WATER
INJECTION
ORIFICE
FLANGES
SA-4380-42

FIGURE 2 ORIFICE GAS/LIQUID CONTACTOR

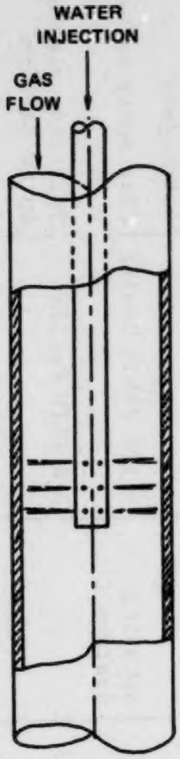

GAS
FLOW
WATER
INJECTION
ORIFICE
FLANGES
SEMICIRCULAR
ORIFICE

SA-4380-41

FIGURE 3 MULTIPLE-ORIFICE SERIES GAS/LIQUID CONTACTOR

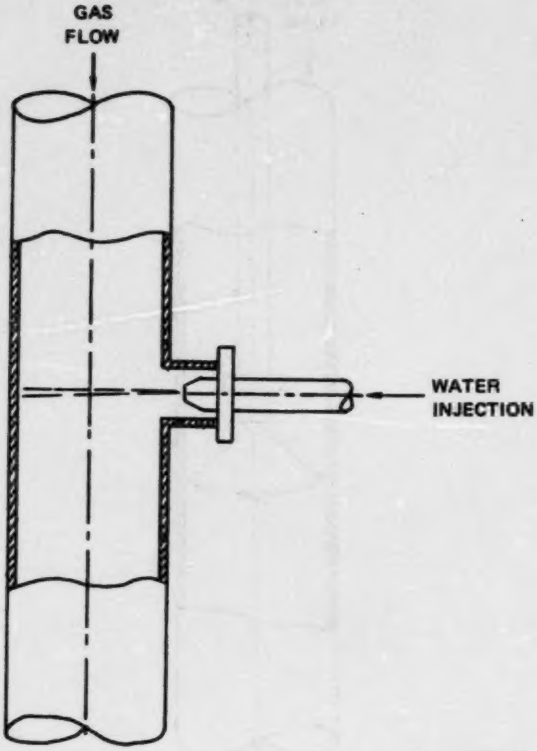
TABLE 2. PRESSURE SPRAY NOZZLES USED FOR GAS/LIQUID CONTACTING

SRI test code	Nozzle manufacturer	Manufacturer's designation	Nozzle type
SS1	SRI	Perforated tube	Multiple solid-stream water jets
SS2	Spraying Systems Co.	H 1/4 U9530 VeeJet	Flat spray pattern
SS3		3/8 G17W FullJet	Full-cone wide angle spray pattern
SS4		8686-1/4-1.5-180° DeflectoJet	Deflected type hollow-cone spray pattern
SS5		1/2 G3030 FullJet	Full-cone spray pattern, 30°, injector type
SO		3/8 G15 FullJet	Full-cone spray pattern


WATER INJECTION
GAS FLOW

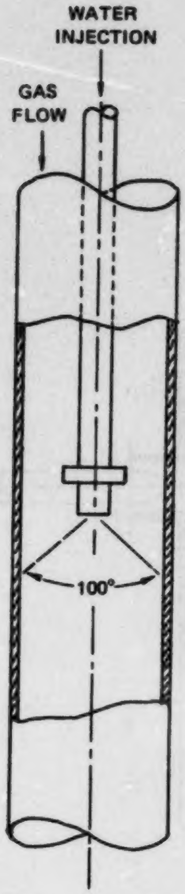
SA-4380-43

FIGURE 4 SPRAY GAS/LIQUID CONTACTOR
Configuration SS1


GAS
FLOW
WATER
INJECTION

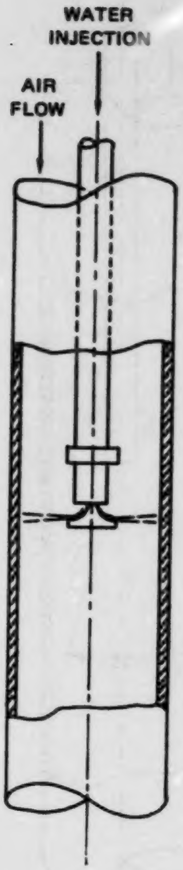
SA-4380-44

FIGURE 5 SPRAY GAS/LIQUID CONTACTOR
Configuration SS2


WATER
INJECTION
GAS
FLOW
100°

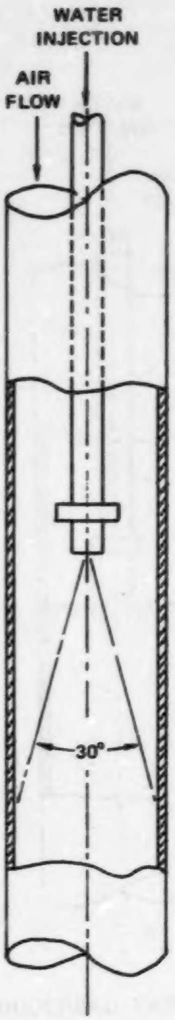
SA-4380-45

FIGURE 6 SPRAY GAS/LIQUID CONTACTOR
Configuration SS3


WATER INJECTION
AIR FLOW

SA-4380-46

FIGURE 7 SPRAY GAS/LIQUID CONTACTOR
Configuration SS4


WATER
INJECTION
AIR
FLOW
30°

SA-4380-47

FIGURE 8 SPRAY GAS/LIQUID CONTACTOR
Configuration SS5

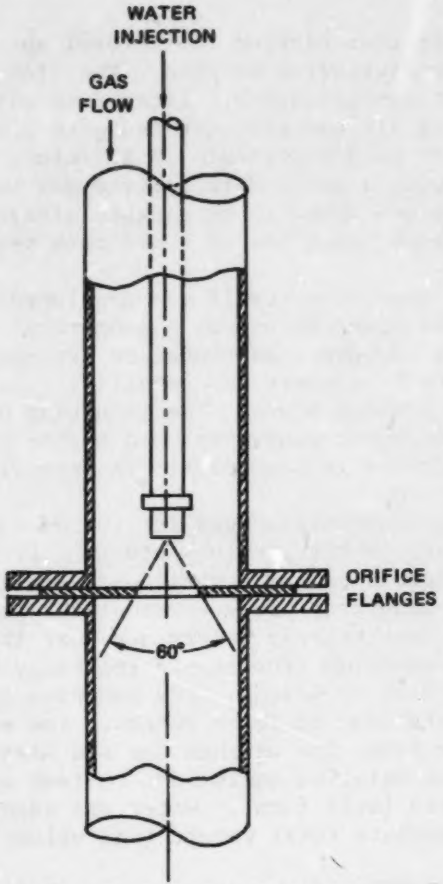

WATER INJECTION
GAS FLOW
ORIFICE FLANGES
60°
SA-4380-48

FIGURE 9 SPRAY-ORIFICE GAS/LIQUID CONTACTOR

concentrically within the 15.2-cm (6-inch) riser that carried the main air flow upward to the scrubber. Another small flow of drying air also entered the lower end of the conical diffuser section through the annular space around the 1-inch pipe carrying the mist. The mist and the drying air mixed in the diffuser section, where the water was evaporated from the droplets, leaving solid aerosol particles. The resulting aerosol stream emerging from the end of the diffuser then mixed with the main air stream, which flowed through the annular space between the upper end of the diffuser and the 15.2-cm riser.

The sweep air that carried the aerosol out of the nebulizer was metered with a critical-flow orifice. The flow rate used was 6 liters/min with the coarsest aerosol and 2.1 liters/min with the two finer aerosols. The aerosol drying air was also metered with a critical-flow orifice to a constant rate of 84.9 liters/min (3 ft^3/min). The drying air stream could be heated with a small direct-fired gas burner if necessary. However, the dry air was found to be capable of evaporating the water from the droplets without being heated above room temperature.

The aerosol generator itself was developed by Stanford Research Institute, and was based on use of a commercial ultrasonic nebulizer to produce the mist. However, an elaborate arrangement of auxiliary equipment was necessary to convert the nebulizer into an aerosol generator suitable for the present study. The resulting unit was vastly superior to an earlier ultrasonic generator used in the previous study.[6] The generator is described in more detail in Appendix B.

The ammonium fluorescein used for the aerosols had already proved highly satisfactory in the previous study.[6] It was desired to produce three similar aerosols having nominal mass-median diameters of 0.4, 0.7, and 1.5 μm. The generator produces droplets with a nominal mean size of about 6-8 μm. It was thereby determined that the three aerosols could be produced from ammonium fluorescein solutions having concentrations of 0.01%, 0.1%, and 1.0% by weight. The ammonium fluorescein was first prepared at a concentration of 1% by weight. The appropriate amount of fluorescein (acid form) was weighed out and dissolved in a quantity of ammonium hydroxide solution equivalent to four moles of ammonium ion per mole of fluorescein (acid form). Water was added to make up the solution to the appropriate total weight (and volume).

In the first phase of the project, the 0.1% and 0.01% solutions were prepared by diluting the 1.0% solution 10 to 1 and 100 to 1, respectively, with 0.3N ammonium hydroxide. It was then discovered that generation of the aerosol from the 0.01% solution was being affected by contaminants--apparently silica dissolved in the ammonium hydroxide solution. Thereafter, the 0.1% and 0.01% solutions were prepared by diluting the 1% stock solution with distilled water instead of 0.3N ammonium hydroxide. The behavior of the generator and aerosols is discussed in Section 6.

AEROSOL SAMPLING AND CHARACTERIZATION

The aerosol was sampled at the inlet and the outlet of the scrubber (see Figure 1). At the outlet, the sample was collected on a 25-mm Nuclepore membrane filter (0.6-µm pore size) held in a Nuclepore holder that was mounted in the scrubber outlet line. The inlet piece of the filter holder was machined out to expose almost the entire effective area of the membrane filter directly to the incoming gas, and the holder was turned to face directly into the gas stream being sampled. At the inlet of the scrubber, the aerosol sample was obtained with the miniscrubber (described below), and the air sample was drawn out of the duct through a sampling nozzle that consisted of a 90° ell of 2.54-cm stainless steel tubing. The open end of the ell faced directly into the gas stream. No effort was made to sample isokinetically at either inlet or outlet because the aerosols were too small for sampling to be influenced appreciably by inertial effects. The air flows through the sampling trains were metered with critical-flow orifices. Vacuum was supplied by a mechanical vacuum pump. The gas sampling rates were 16 liters/min at the scrubber inlet and 6.5-7.5 liters/min at the outlet.

The sampling techniques used in this investigation were essentially the same as those used in the earlier study,[4] in which it was determined that the average error in aerosol sampling did not exceed 5%-6%. No additional determinations of sampling errors were made in this investigation.

The miniscrubber consisted of four nominally identical Greenburg-Smith impingers (Ace Glass Inc. No. 7536) connected in series. A diaphragm-type differential pressure gauge (Dwyer Magnehelic) was used to measure the total pressure drop across the four impingers, which was standardized at 200 cm WC. Because of minor differences in the impinger nozzles and/or impact plates, the pressure drops of individual impingers showed variations of up to about 14%. These variations were taken into account in the correlation of miniscrubber sample data. Identical quantities of liquid (100 ml of 0.3N ammonium hydroxide solution) were used in each impinger. The ammonium hydroxide solution was used to ensure that the collected aerosol particles would go into solution, since the monoammonium fluorescein aerosol material has a very low solubility in pure water.

A 47-mm Nuclepore filter (0.4-µm pore size) was used to collect the aerosol that penetrated the impinger train. From analyses of the aerosol collected in each impinger and on the filter, it was possible to determine the collection at each stage of the miniscrubber as well as the overall efficiency. The methods of presenting and using the miniscrubber test data are described and discussed in Section 6.

Aerosol particle size was studied by two methods. Direct visual indications of aerosol size and character were obtained with a scanning electron microscope (SEM). Samples were collected on Nuclepore membrane filters having either 0.2- or 0.4-µm pores. A sample was then prepared for study by cutting a section out of the center portion of a membrane and mounting it on an aluminum SEM stage, fixing it in position with conductive silver paint. The prepared sample was coated with a thin film of gold-palladium by vapor deposition to render the surface conductive. The sample was scanned with the SEM to locate one or more representative fields. Then photomicrographs were made at a number of magnifications. From these it was possible to estimate the range of particle sizes. It was also possible to make a rough visual judgment of the probable mass-median diameter, but no attempt was made to determine the distributions by making particle counts.

Measurements of the particle-size distributions of the aerosols were made with an eight-stage Andersen nonviable cascade impactor (manufactured by Andersen 2000 Inc.) equipped with glass impaction plates. The impactor was followed by a 47-mm Nuclepore filter with 0.4-μm pore size. The air flow rate was measured with a Sprague dry gas meter and was controlled with a valve in the vacuum line downstream of the impactor, backup filter, and meter. Air flow rates were set at the beginning of a run and held constant throughout the run. The rates varied from about 15 to 25 liters/min and produced a total pressure drop across the impactor and the backup filter of 1-15 cm of mercury. The calculated flow rates were corrected for the temperature and pressure existing at the meter.

The initial impactor studies were made with an older seven-stage Andersen unit, using dry glass impaction plates. The early results indicated that the aerosols were finer than would be anticipated from the SEM examinations, suggesting the possibility that bouncing and reentrainment of the aerosol particles may have been taking place. Later, when the new eight-stage impactor was substituted, the collection plates were coated with Dow-Corning silicone stopcock grease. The coating was applied by painting the plates with a 10% solution of the grease in carbon tetrachloride, using a soft camel's hair brush. Two applications were made, with an intervening drying period, and the plates were allowed to dry under a clean hood. As observed under a microscope, the dried grease surfaces were not smooth; however, no attempt was made to alter the surface after the grease was applied.

Trials were also made with the impaction plates covered with sticky-faced paper. However, this method was abandoned as inferior to use of the greased plates.

AEROSOL ANALYSIS

Fluorimetric analyses of the ammonium fluorescein aerosol material were made with an Aminco-Bowman Spectrophotofluorometer with a xenon lamp (Catalog Numbers 4-8202 and 4-8202B). The unit was equipped with monochromators for both excitation and emitted light. Instrument settings used in the analyses were as follows:

- Excitation wave length--482 nm.
- Emission wave length--540 nm.
- Primary slits--full open.
- Secondary slits--5 mm.
- Photomultiplier slit--0.1 mm.
- Meter multiplier setting--to give transmittance reading between 30% and 90%.

A Corning 3-69 filter was used to eliminate interferences with excitation wave length.

The transmittance of the ammonium fluorescein solutions followed Beer's Law at concentrations between 4×10^{-7} g/cm^3 and 1×10^{-10} g/cm^3. The fluorescence was markedly a function of pH, increasing by a factor of 25 as the pH was increased from 4 to 10. Samples were dissolved in a solution of ammonium hydroxide having an initial pH of 11.

Samples for analysis (1.5-2 cm^3) were placed in a clean, dry cuvette (fused quartz) of rectangular cross section. If the resulting concentration of ammonium fluorescein was above the preferred range for analysis, the sample was diluted with an ammonium hydroxide solution of pH 11.

Since the liquid from the impingers was a 0.3N solution of ammonium hydroxide (pH 11), it could be analyzed directly. All the internal glass surfaces of an impinger were washed, and the washings were included with the liquid from the impinger. A single washing of a Nuclepore filter was sufficient to remove the aerosol deposit; therefore, filters were simply immersed in 10 cm^3 of the ammonium hydroxide solution and agitated.

With the Andersen impactor, each orifice plate and each dry collection plate was washed in 20 cm^3 of the ammonium hydroxide solution. The orifice plates were washed and the washings analyzed to determine wall losses.

When grease-coated impaction plates were used, a plate was washed with carbon tetrachloride and agitated until no remaining grease could be seen on the plate. A portion of ammonium hydroxide was then added to the carbon tetrachloride washings and the two fluids were agitated together. The ammonium fluorescein is essentially insoluble in the carbon tetrachloride. Since the carbon tetrachloride and the ammonium hydroxide are immiscible, the ammonium fluorescein was extracted from the carbon tetrachloride into the aqueous solution phase, which was then separated and analyzed.

Experience with replicated analyses indicated that the error in ammonium fluorescein analysis did not exceed 1% except in the very smallest samples, for which the error was somewhat larger.

GENERAL SCRUBBER TEST PROCEDURE

All tests with the scrubber were made with air and water at ambient temperatures. The average room air temperature was about 25°C. When the scrubber operating conditions were adjusted as desired and operation of the scrubber and aerosol generator was steady, the samplers were operated for a measured time interval (generally 5-20 minutes, depending on the aerosol used). All air flow rates in the scrubber and the samplers were referred to the chosen standard state, 25°C and 1 atm pressure, which was approximately the average condition in the laboratory.

SECTION 6

RESULTS AND DISCUSSION

AEROSOL CHARACTERIZATION WITH THE MINISCRUBBER

Since the basic experimental approach was absolutely dependent on the ability to produce consistent and reproducible test aerosols, it was necessary to have an appropriate method for determining the consistency and reproducibility of the aerosols being generated. The available methods for particle-size analysis are generally slow or complicated, or both, and are subject to a variety of errors and uncertainties. Also, a given method is commonly not applicable over the complete spectrum of particle sizes that may be encountered. For the present study, it was essential that the method for monitoring the consistency of the aerosols should be simple, rapid, and reliable. Fortunately, it was not necessary that the monitoring method give an absolute measurement of particle-size distribution; it was sufficient that the technique reveal changes in the aerosols and give some idea of the magnitude of the changes.

In previous investigations, it was observed that with scrubbers using gas-phase contacting power, the performance of the scrubber at a given contacting power or, better, over a range of contacting power was a very sensitive indicator of differences in aerosols. The contacting power/efficiency relationship does not, of course, provide an absolute measurement of particle size or particle-size distribution, although it does give a relative indication of particle size. The use of the miniscrubber was not predicated on any assumption that the relationship of collection efficiency to pressure drop should necessarily be the same as that for larger scrubbers of the same or different types. The only assumption was that if the miniscrubber was always operated identically, it should always give the same efficiency on the same aerosol.

The use of multiple stages improved the aerosol characterization. By expressing the stage efficiencies in terms of the number of transfer units, which are additive, and plotting the cumulative number of transfer units as a function of the cumulative gas pressure drop, a complete scrubber performance curve could be generated from one test run. The results were equivalent to four scrubber efficiency determinations at different pressure drops obtained by using combinations of one, two, three, and four scrubber units (impingers) in series.

As is shown below, the four data points commonly defined with high precision a straight line on a log-log plot. The number of transfer units obtained from a stage is qualitatively indicative of the particle size of the aerosol entering that stage. The slope of the curve should logically be related to the particle-size distribution. For an absolutely monodisperse aerosol, each identical scrubber stage should give the same collection efficiency, and the slope of the performance curve should be unity. This conclusion further assumes, however, that the aerosol is not hygroscopic and does not grow between stages by absorption of moisture, and that the temperature and other conditions of the gas stream remain constant throughout the scrubber train. If the aerosol has a distribution of particle sizes, the preferential collection of the larger particles will cause a reduction in the average particle size of the aerosol entering each succeeding stage, and hence a drop in the collection efficiency of each succeeding stage; this is the behavior actually encountered with the aerosols generated. In such a case, if the performance curve is a straight line (as has been the case in practice), the slope will be less than unity.

In early work,[5] it was hypothesized that the slope of scrubber performance curves in general should probably be determined by particle-size distribution. However, the results of work both at SRI[6] and elsewhere[5] have shown enough anomalies to make it highly unlikely that the slope is determined only by the particle-size distribution, although this may be more nearly true of the miniscrubber performance curves.

To avoid confusion in references to the performance curves of the pilot-plant scrubber and the miniscrubber, it was desirable that the curve for the miniscrubber be designated by another term. Since the miniscrubber performance curve is presumably characteristic only of the aerosol, the curve was termed the "aerosol signature curve," or simply as the "aerosol signature."

TEST AEROSOL GENERATION

The ultrasonic aerosol generator was first tested extensively to determine the stability and reproducibility of the aerosol production. This part of the work was supported by SRI's Internal Research and Development funds. Tests were made to determine the degree of interchangeability of different generator crystals and power sources. All the tests were made with 1.0% ammonium fluorescein solution, and the reproducibility of the aerosol was judged from the aerosol signature curves. The tests and results are discussed in detail in Appendix B. In brief, it was found that different generator crystals and power sources were interchangeable, and that those originally put in use could therefore be replaced if they should fail during the experimental program. The aerosol produced did vary, but within a range that appeared likely to be tolerable. The remainder of the characterization of the aerosol (designated as Aerosol D) was carried out in conjunction with determination of the baseline performance curves of the orifice scrubber. It was then found that the performance of the miniscrubber was more sensitive to variations in the aerosol than was the orifice scrubber, which provided some margin of safety in the experimental program.

Originally, it had been hoped that the aerosol consistency might be sufficient that only periodic checking with the miniscrubber would be necessary, and that the aerosol concentration at the bench-scale scrubber inlet could normally be determined with a filter only. However, experience demonstrated that full confidence in the results required obtaining the signature of the aerosol for each scrubber efficiency test. Thereafter, the scrubber inlet sample was taken with the miniscrubber in all cases. This procedure greatly increased the number of samples that had to be prepared and analyzed.

The nominal mean diameters of the test aerosols were chosen to give a factor of approximately 2 between the sizes of succeeding aerosols (see Table 3). Aerosol E was similar in size to the aerosol used in the previous study of condensation phenomena in scrubbing.[6] Preliminary verification of the approximate particle sizes of the aerosols was made from studies of samples with the SEM. Because the particles were spherical (except as noted below) and of relatively low density (1.35 g/cm^3), there was reasonable agreement between the actual diameters as observed in the electron micrographs and the aerodynamic diameters as determined with the cascade impactor. The density of the monoammonium fluorescein was not measured but was taken from a paper by Stöber and Flachsbart.[14]

The larger aerosols, D and E, were composed entirely of spheres (see Figures 10 and 11). However, the first nominal 0.4-µm aerosol produced, Aerosol F, was composed of irregular and flattened particles (see Figure 12), so that the equivalent diameters could not be judged by visual examination. Aerosol F was also far more erratic than Aerosols D and E, as was shown by the signatures and the scatter in the orifice scrubber performance data (discussed below). Upon study, it became evident that contamination of the 0.01% ammonium fluorescein solution being nebulized was responsible. Trial generation of aerosols was carried out with solutions in the concentration range from 0.1% to 0.01%, and it was found that the departure of the particles from spherical shape was a trend appearing as the concentration was reduced below 0.05%. The most likely contaminant appeared to be silica dissolved from glass containers by the ammonium hydroxide solution. Because the 0.01% solution was produced by dilution of the 1% stock solution with 0.3N ammonium hydroxide, the ratio of ammonium hydroxide--and presumably of any dissolved silica--to ammonium fluorescein was much greater in the dilute solution.

Some confirmation of this hypothesis was obtained from X-ray dispersion studies of the aerosol samples being examined in the SEM. Qualitatively, Aerosol F was found to have a much higher silica content than did Aerosol D. In addition, a test was made by nebulizing 0.3N ammonium hydroxide solution in the aerosol generator and sampling the air stream with a Nuclepore filter for a prolonged period. Examination of the filter sample with the SEM showed irregular particles that may have consisted of ammonium silicate or silica. From examination of comparable samples with the SEM, it was crudely estimated that the mass of the contaminant material present in Aerosol F might have been of the order of one-tenth that of the ammonium fluorescein. Such a quantity of silica (or even two or three times that amount) would have relatively little

TABLE 3. TEST AEROSOL CHARACTERISTICS

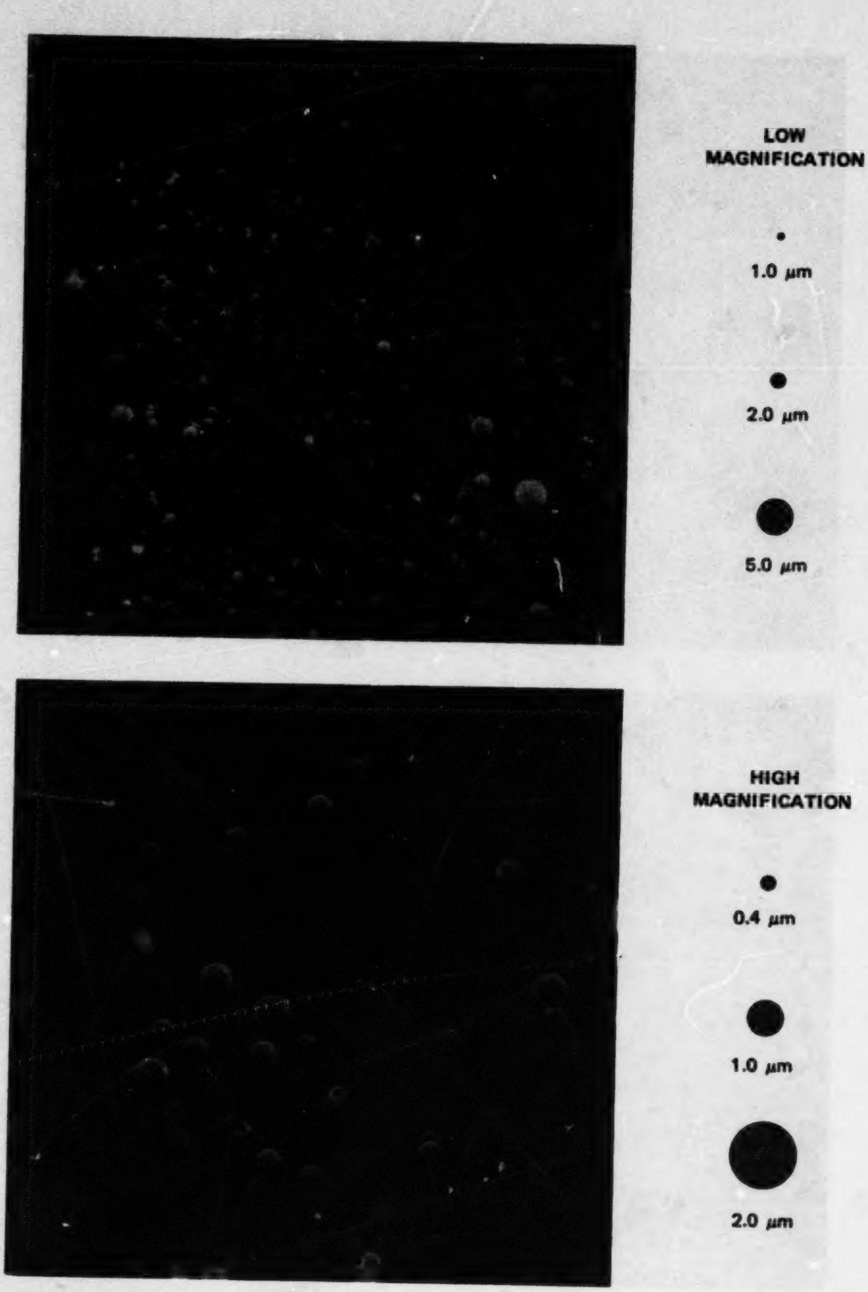
Code designation	Nominal mean diameter (μm)	Particle-size range[a] (μm)	Mass-median diameter[b] (μm)	Standard geometric deviation[c]
D	1.5	0.2 - 5	1.05	1.58
E	0.7	0.15 - 2.6	0.68	1.69
F	0.4	0.1 - 2.3[d]		
G	0.4	0.07 - 1.3	0.42	

[a] Observed from electron micrographs.

[b] Measured with cascade impactor.

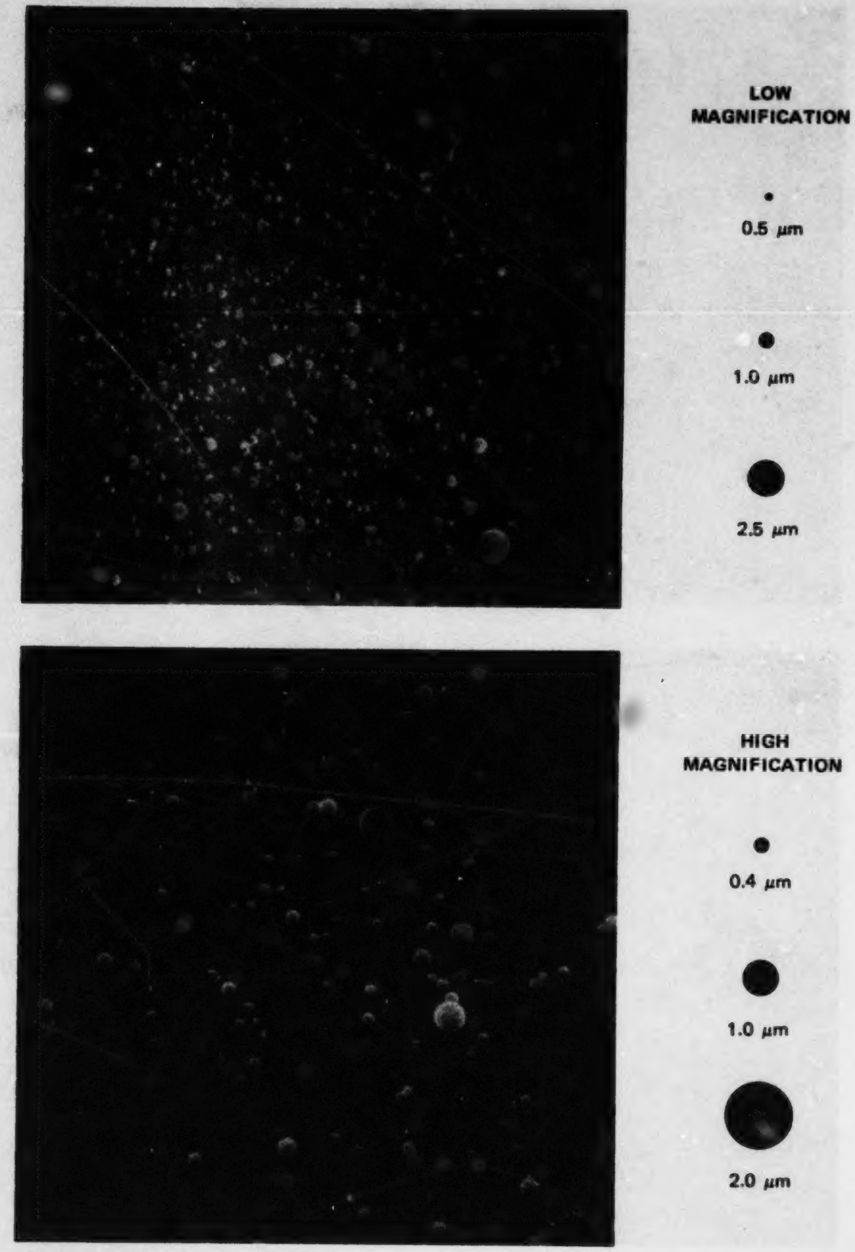
[c] Particle-size distribution taken as log-normal.

[d] Particles flattened.


LOW
MAGNIFICATION
1.0 μm
2.0 μm
5.0 μm
HIGH
MAGNIFICATION
0.4 μm
1.0 μm
2.0 μm

SA-4380-57

FIGURE 10 ELECTRON MICROGRAPH OF AEROSOL D


LOW MAGNIFICATION
0.5 µm
1.0 µm
2.5 µm
HIGH MAGNIFICATION
0.4 µm
1.0 µm
2.0 µm

SA-4380-58

FIGURE 11 ELECTRON MICROGRAPH OF AEROSOL E

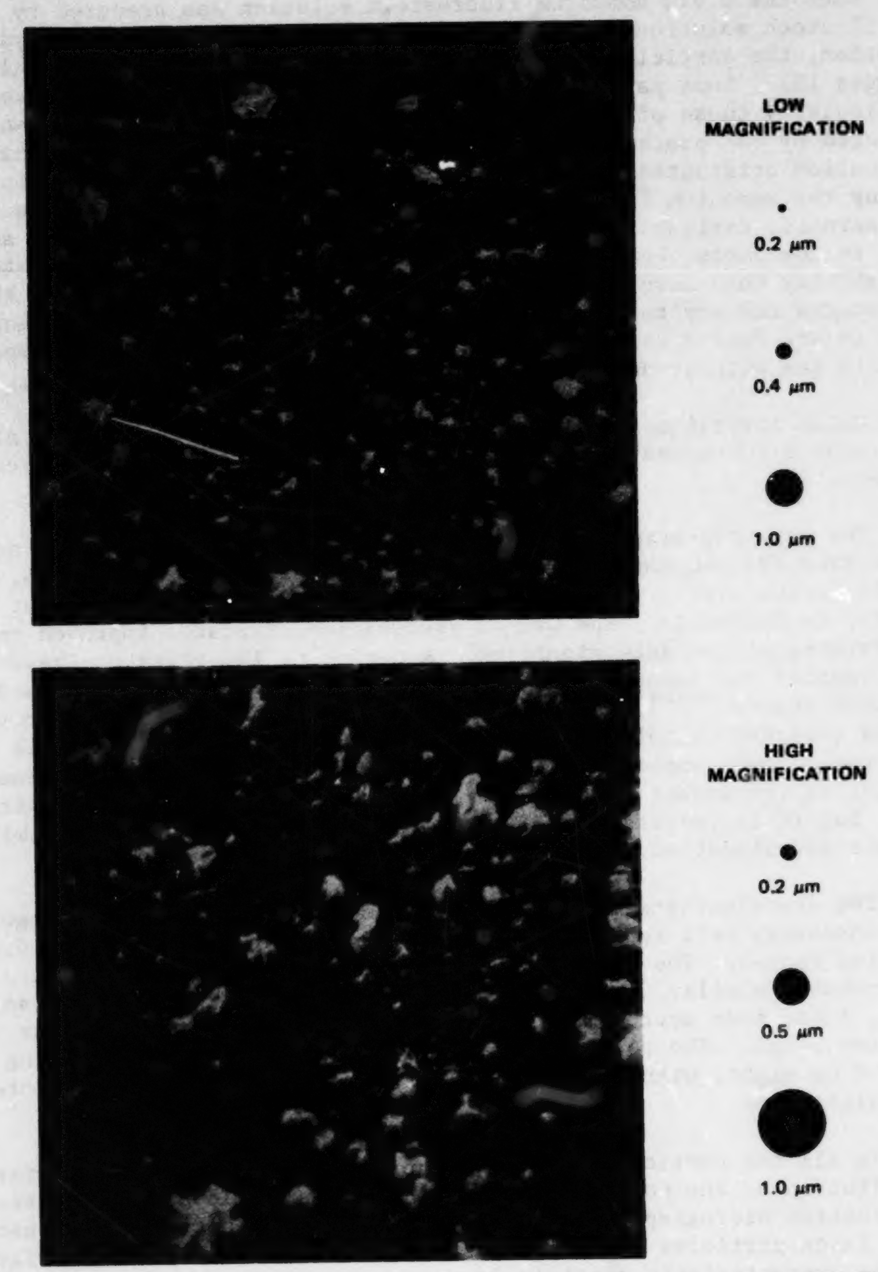

LOW MAGNIFICATION
0.2 μm
0.4 μm
1.0 μm
HIGH MAGNIFICATION
0.2 μm
0.5 μm
1.0 μm
SA-4380-59

FIGURE 12 ELECTRON MICROGRAPH OF AEROSOL F

influence on the size of the aerosol particles, but it evidently did have a dominant effect in determining the particle shape.

When the 0.01% ammonium fluorescein solution was prepared by diluting the 1% stock solution with distilled water instead of ammonium hydroxide solution, the particles generated from it were generally spherical (Figure 13). Some particles of irregular shape were still produced, particularly those of the finest sizes that would presumably be most affected by the presence of the contaminant. Probably the residual contamination originated from the ammonium hydroxide solution used in preparing the ammonium fluorescein from the acid form of fluorescein. The new aerosol, designated as Aerosol G, was generally satisfactory and was used in the subsequent studies. However, Aerosol G did show greater variability than Aerosols D and E, as was shown by variations in the signatures and scatter in the scrubber performance data. It appears that in any future work the ammonium fluorescein should be prepared from ammonia gas without any contact with glass.

Other investigators who have used ammonium fluorescein have also experienced contamination problems with solutions below 0.05% in concentration.[15]

The particle-size distributions of Aerosols D, E, and G, as determined from cascade impactor measurements, are shown in Figures 14, 15, and 16, respectively. The curves are summarized together, without data points, in Figure 17. The use of greased impact plates improved the consistency of the determinations. A number of investigators have noted and reported the tendency for particles to bounce or be reentrained from impactor stages.[16-18] This tendency is accentuated in the higher velocity stages intended to collect the finer particles. The net effect is to make the aerosol appear to be finer than it actually is. The adhesive coating of the impact plates helps to reduce the bouncing or reentrainment, but it is uncertain to what degree these phenomena were eliminated in this investigation.

The distributions of Aerosol D (Figure 14) and Aerosol E (Figure 15) are reasonably well represented as log-normal over the important parts of the size ranges. The actual size distribution of Aerosol G (Figure 16) was probably similar, but most (70%) of the material was finer than that (i.e., finer than approximately 0.5 μm) collectable on the highest velocity impactor stage. The portion of the distribution of Aerosol G lying below 0.8-1.0 μm might, within the precision of measurement, be represented by a straight line.

In all the particle-size distributions, the "spike" in the size distribution of the coarsest 1-2% of the aerosol evidently is fictitious. The electron micrographs of the aerosol samples do not indicate that these large particles actually existed. The indicated particle sizes are the characteristic particle diameters for the impactor stages; that is, the diameter of the particle that should be collected with 50% efficiency. However, smaller particles are also collected although with

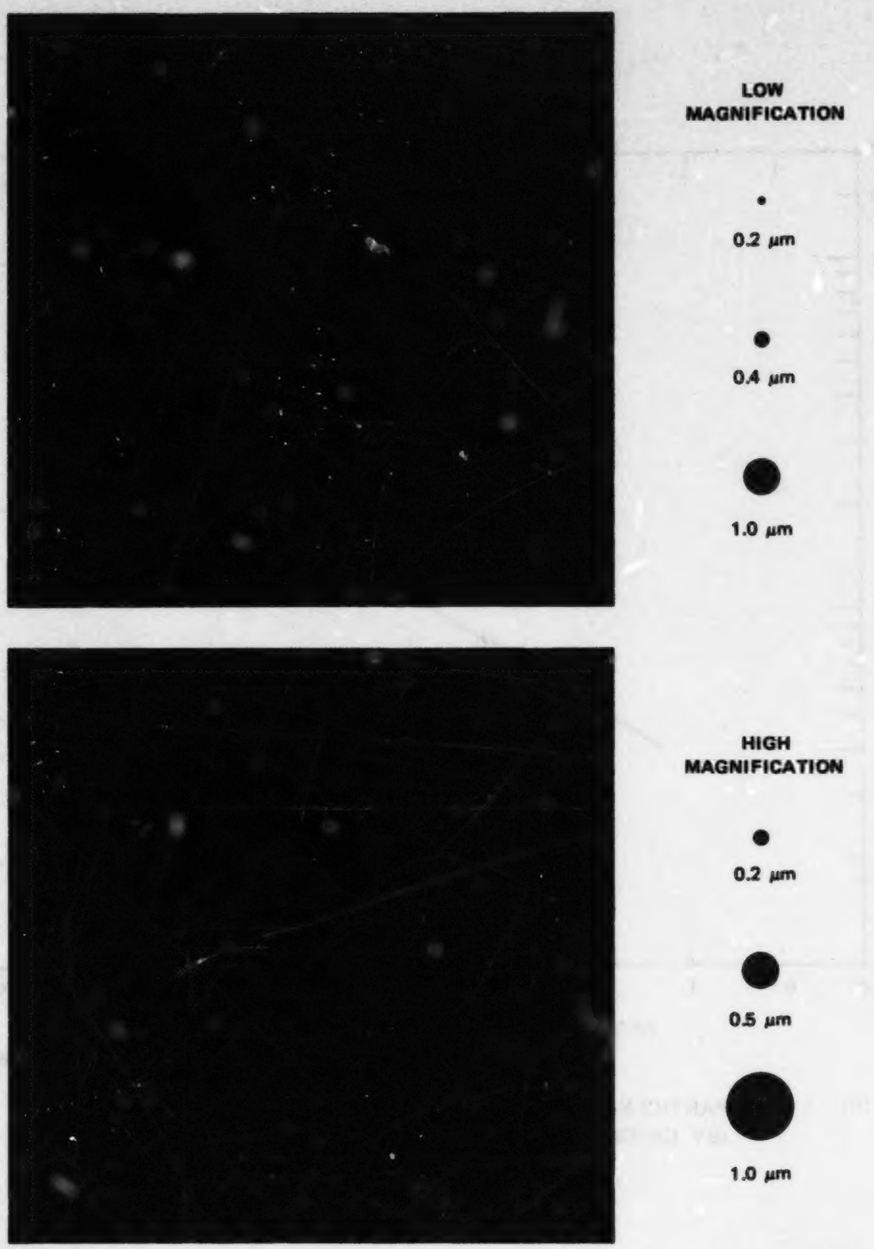

LOW MAGNIFICATION
0.2 μm
0.4 μm
1.0 μm
HIGH MAGNIFICATION
0.2 μm
0.5 μm
1.0 μm
SA-4380-60

FIGURE 13 ELECTRON MICROGRAPH OF AEROSOL G

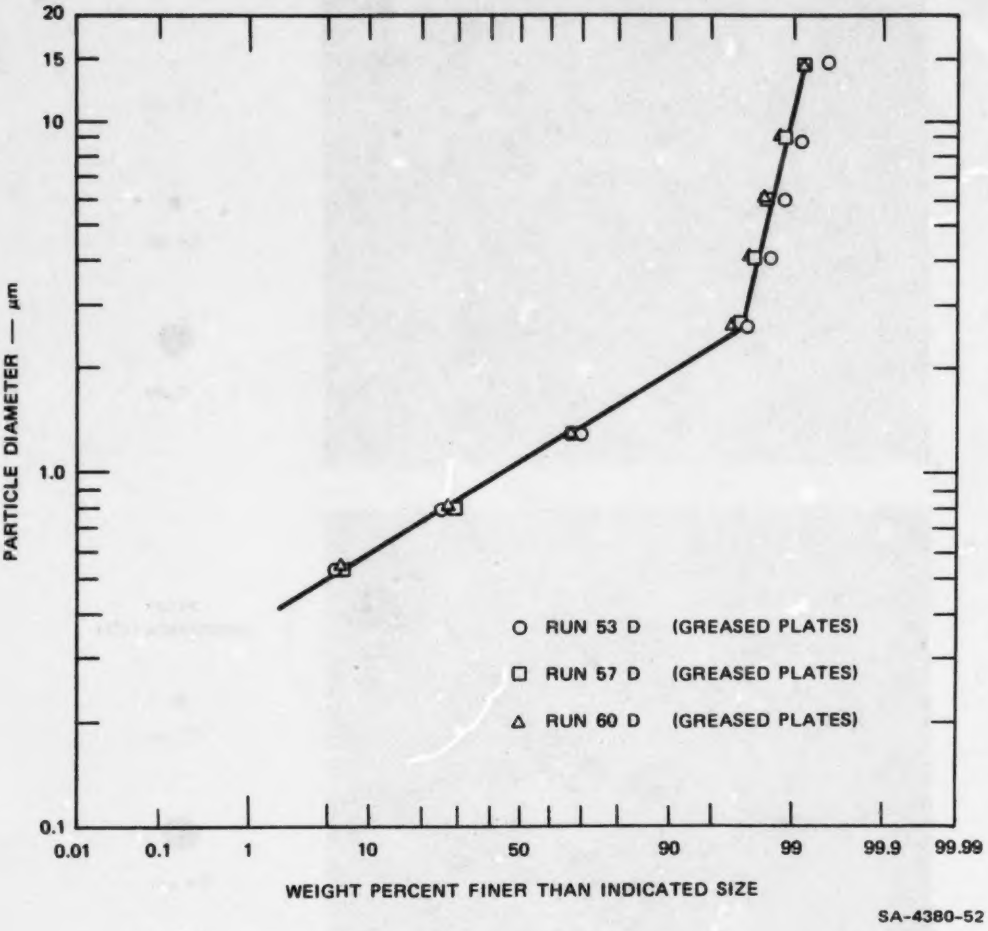
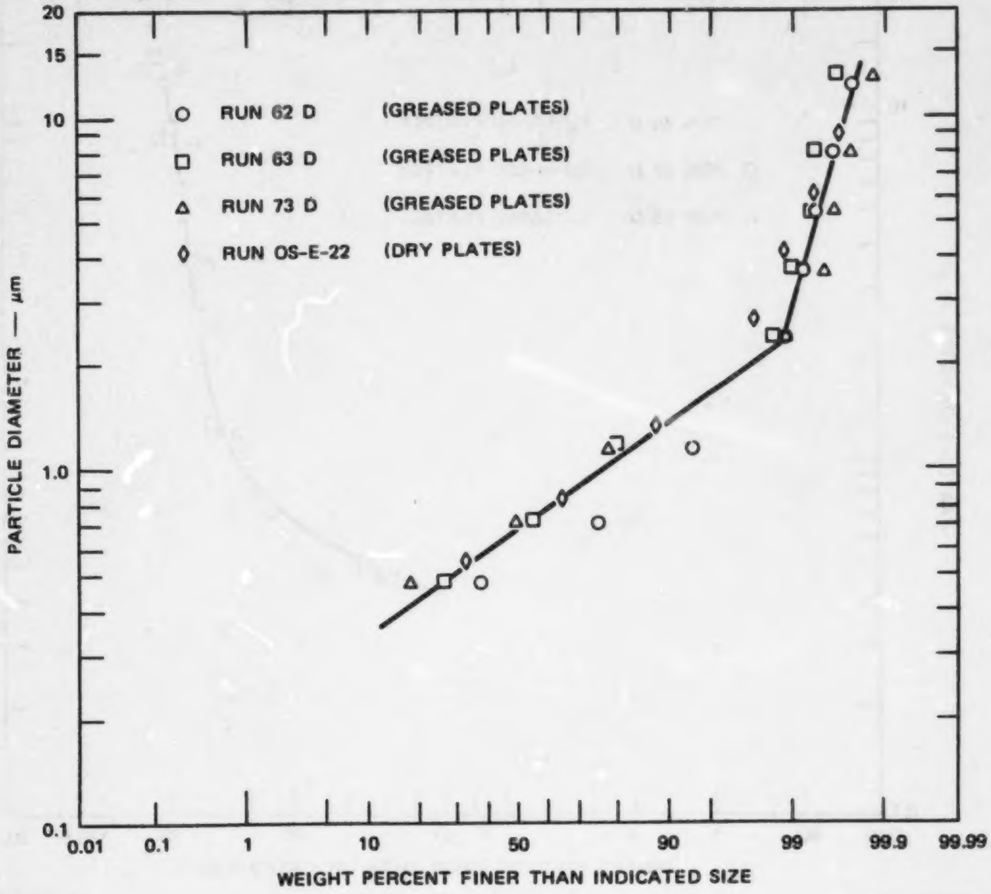
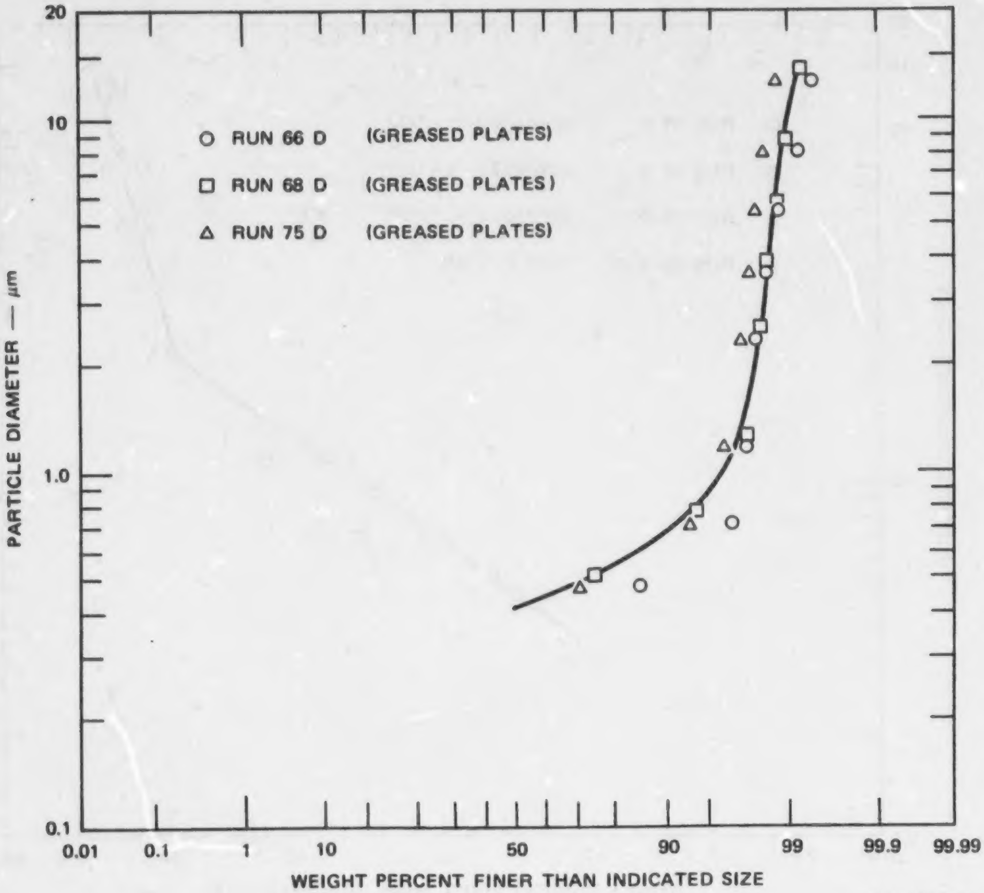


FIGURE 14 PARTICLE-SIZE DISTRIBUTION OF AEROSOL D — MASS BASIS (BY CASCADE IMPACTOR)



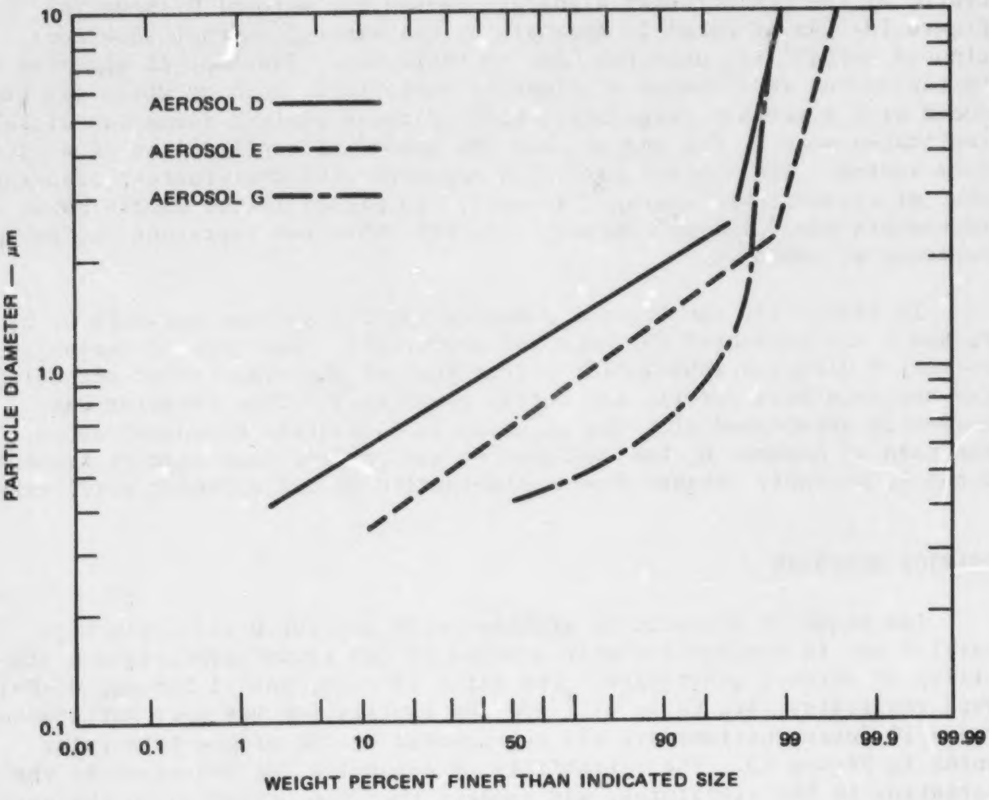
SA-4380-53

FIGURE 15 PARTICLE-SIZE DISTRIBUTION OF AEROSOL E — MASS BASIS (BY CASCADE IMPACTOR)



SA-4380-54

FIGURE 16 PARTICLE-SIZE DISTRIBUTION OF AEROSOL G — MASS BASIS (BY CASCADE IMPACTOR)



SA-4380-55

FIGURE 17 SUMMARY CURVES — PARTICLE-SIZE DISTRIBUTIONS OF AEROSOLS D, E, AND G (MASS BASIS)

lower efficiencies. The total amounts of material collected on these impactor stages were low, and could well be accounted for by collection of small fractions of the coarser particles actually known to be present in the aerosols.

If the curves in Figures 14 and 15 that represent the bulk of the aerosols are extrapolated to the line indicating 99.99% of the total aerosol, the intercepts correspond roughly to the sizes of the largest particles actually observed in the electron micrograph fields (see Table 3).

The variations in the aerosols produced by the generator are illustrated by the miniscrubber signature curves for Aerosol D shown in Figure 18. As is noted in Appendix B, the aerosol did not show continuous variability over the band of variation. Instead, it appeared to be reproduced in a number of discrete variations, each of which was produced with a certain frequency. Each of these variant forms was closely replicated when it did appear, but the number of replications of a given form varied. The variant form that appeared with the greatest frequency was, of course, the "average" aerosol. In Figure 18 the middle curve represents the "average" variant, and the other two represent the extreme variants encountered.

In Figure 19, the signature curves for the average Aerosols D, E, F, and G are presented together for comparison. The mode of variation of Aerosol F differed substantially from that of the other three aerosols; the variants were erratic and poorly replicated. This behavior was evidently associated with the solution contamination discussed above. In the case of Aerosol G, the variability was greater than that of Aerosols D and E, probably because some contamination of the solution still existed.

ORIFICE SCRUBBER

The tests of the orifice scrubber with Aerosol D initially were carried out in conjunction with studies of the reproducibility and stability of aerosol generation. The first 10 runs, OS-D-1 through OS-D-10, were replicates (see Table 4),* and the replication was very satisfactory. These 10 determinations are all represented by the single triangular point in Figure 20. The variability of Aerosol D, as indicated by the variation in the signatures, was greater than the variation in the performance of the orifice scrubber. Later variations in the aerosol or in the determination of orifice scrubber efficiency, or in both, were greater,

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*In all the tabulations of scrubber performance data (Tables 1-19) the results were transcribed from computer printouts, which carried the numbers to four significant digits. However, the presence of the four digits is not to be interpreted as an indication of precision; the data are actually valid to no more than three significant figures.

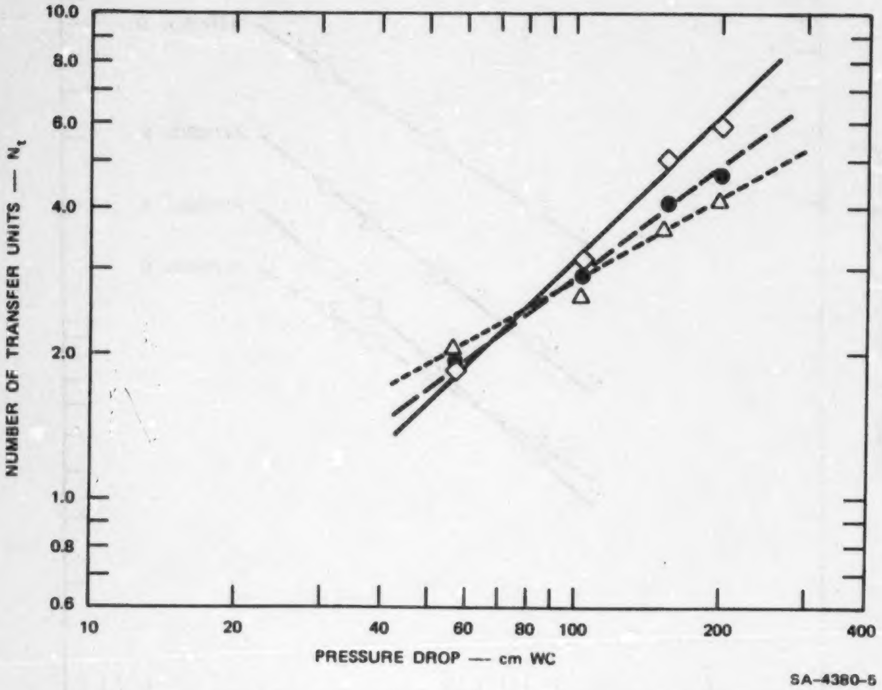

FIGURE 18 VARIATIONS IN AEROSOL D INDICATED BY MINISCRUBBER SIGNATURE CURVES

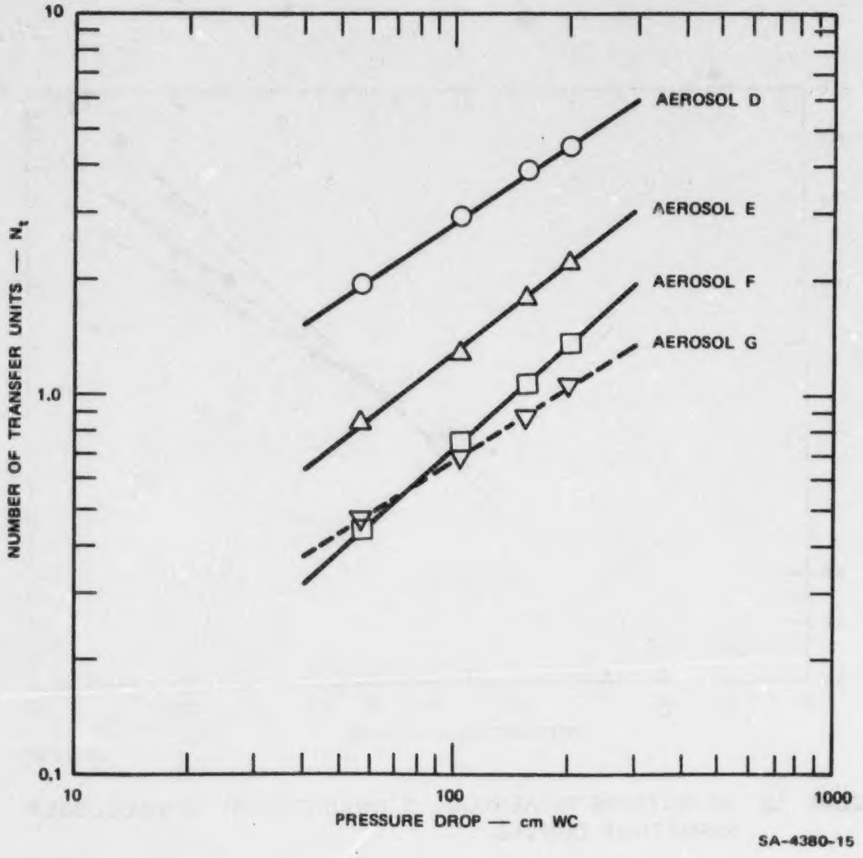

FIGURE 19 MINISCRUBBER SIGNATURE CURVES FOR AEROSOLS D, E, F, AND G

TABLE 4. PERFORMANCE OF ORIFICE SCRUBBER ON AEROSOL D

Test code	Contactor orifice size (cm)	Gas flow rate (std m^3/min)	Gas velocity in orifice (m/sec)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3) In	Aerosol concentration (mg/std m^3) Out	Collection efficiency (%)	Transfer units (N_t)
OS-D											
1	2.54	2.370	77.96	1.55	101.6	2.768	9.004	3.799	0.1267	96.[illegible]	3.401
3		2.370	77.96	1.55	101.6	2.768	8.419	3.552	0.1294	96.36	3.313
4		2.368	77.89	1.57	101.5	2.765	7.784	3.287	0.1140	96.53	3.361
5		2.368	77.89	1.57	101.5	2.765	7.983	3.371	0.1135	96.63	3.391
6		2.368	77.89	1.57	101.5	2.765	8.038	3.394	0.1166	96.57	3.371
7		2.385	78.45	1.56	102.6	2.795	7.582	3.179	0.1138	96.42	3.330
8		2.385	78.45	1.56	102.6	2.795	7.925	3.323	0.1138	96.58	3.375
9		2.385	78.45	1.56	102.6	2.795	7.497	3.144	0.1138	96.38	3.319
10		2.385	78.45	1.56	102.6	2.795	7.582	3.179	0.1152	96.38	3.319
11		2.340	76.97	1.617	98.89	2.694	4.714	1.788	0.07262	95.94	3.203
12		2.349	77.26	3.867	151.0	4.114	2.714	1.155	0.01702	98.53	4.218
13		1.912	62.9	1.386	59.6	1.624	4.226	2.21	0.2766	87.48	2.078
14		2.384	78.4	5.558	189.6	5.166	2.243	0.9411	0.008652	99.08	4.689
15		1.604	52.75	20.39	246.5	6.716	2.315	1.444	0.007716	99.47	5.232
16		1.800	59.21	8.957	127.3	3.469	3.313	1.841	0.0383	97.92	3.872
17		1.347	44.29	11.24	79.92	2.177	4.934	3.664	0.1217	96.68	3.405
18		1.550	51.0	2.441	44.82	1.231	5.747	3.706	0.4389	88.16	2.134
19		1.214	39.92	3.119	29.70	0.8155	5.524	4.552	0.9138	79.93	1.606
20		0.9997	32.88	3.786	19.48	0.5350	5.65	5.652	2.035	63.98	1.021
21		1.141	37.52	45.39	290.6	7.915	3.092	2.71	0.007705	99.72	5.863
22		1.449	47.67	2.611	40.17	1.103	5.436	3.75	0.4085	89.11	2.217
23		1.141	37.52	3.318	25.69	0.7054	4.651	4.077	1.149	71.83	1.267
24		1.122	36.90	0.337	17.93	0.4924	5.135	4.577	5.065	--	--
25		1.577	51.88	20.73	239.1	6.513	1.966	1.246	0.008675	99.30	4.968
26	3.81	3.166	46.28	2.391	34.48	0.9469	5.086	1.606	0.356	77.84	1.507
27		2.63	38.44	2.879	25.0	0.6865	4.985	1.896	0.623	67.14	1.113
28		2.213	32.36	3.42	14.44	0.3965	5.392	2.436	1.309	46.28	0.6214
36	2.54	0.8635	28.4	74.96	306.1	8.339	4.006	4.64	0.01377	99.70	5.820
37		0.8322	27.37	77.77	296.7	8.081	3.785	4.548	0.009952	99.78	6.125
38		0.8836	29.06	73.25	300.7	8.192	4.037	4.568	0.009374	99.79	6.189
39		1.447	47.58	10.47	86.69	2.362	4.685	3.239	0.08766	97.29	3.610
40		1.347	44.29	10.68	75.59	2.059	4.556	3.384	0.06979	97.94	3.881
41		1.248	41.06	12.13	64.07	1.745	4.82	3.861	0.2071	94.64	2.926
42	3.81	2.945	43.06	2.57	30.00	0.8171	5.229	1.775	0.4284	75.88	1.422
43		2.699	39.45	2.805	25.77	0.7021	5.231	1.938	0.5654	70.83	1.232
44		2.223	32.49	3.406	18.36	0.5001	5.21	2.344	0.9739	58.45	0.8783
45		2.058	30.09	3.677	15.43	0.4203	5.121	2.488	1.214	51.19	0.7173
46		2.637	38.55	5.741	40.94	1.115	5.851	2.219	0.3004	86.45	1.999
47		2.637	38.55	5.741	40.94	1.115	15.56	5.898	0.722	87.75	2.100
49		3.004	43.92	10.77	96.04	2.616	9.854	3.280	0.9787	97.02	3.512
50		2.703	39.51	11.97	82.63	2.251	11.98	4.433	0.1626	96.33	3.306
51		1.850	27.04	17.50	51.47	1.402	24.76	13.39	0.6028	95.50	3.100
52		1.541	22.52	21.00	41.04	1.118	14.47	9.392	1.212	87.10	2.048
54		2.900	42.40	11.16	94.96	2.587	3.473	1.198	0.03972	96.68	3.406
55		2.630	38.45	12.30	79.92	2.177	4.803	1.826	0.07858	95.70	3.146
56		1.757	25.69	18.42	47.41	1.291	5.651	3.216	0.3589	88.84	2.193
57		1.639	23.95	19.75	42.81	1.166	5.751	3.510	0.4738	86.50	2.003
58		1.938	28.33	1.953	9.758	0.2658	5.409	2.791	1.907	31.70	0.3812

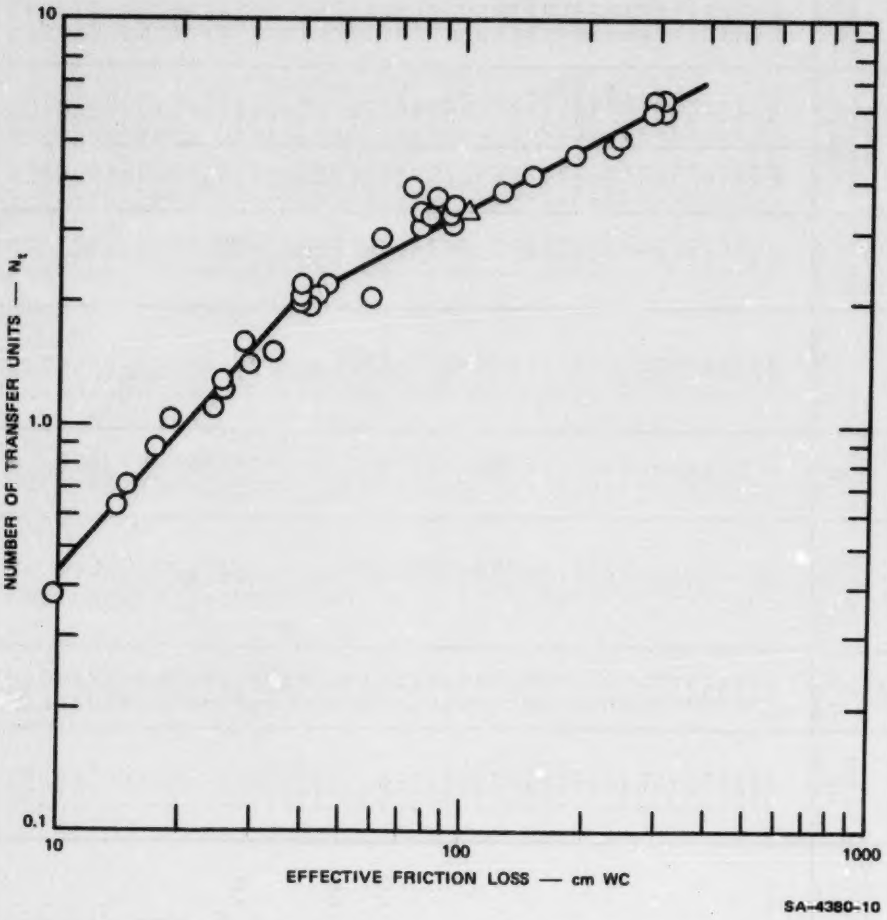

FIGURE 20 ORIFICE SCRUBBER PERFOMANCE CURVE FOR AEROSOL D

as indicated by the scatter of the data in Figure 20. However, these variations were considered tolerable, and the performance curve was well defined. The appearance of the two-branch performance curve is notable. The same phenomenon had appeared under some conditions in the earlier study with the same scrubber and a similar ammonium fluorescein aerosol.[6] However, the finding had been clouded by the instability of the aerosol generator and the resulting problems of data interpretation. It would obviously be possible to fit a single curved line to the data points of Figure 20. However, past experience has shown scrubber performance curves to be well represented by straight lines, and the data here are certainly well represented by the two straight lines.

The energy consumption (or dissipation) was represented in these tests by the "effective friction loss," expressed for convenience in units of centimeters of water. The values used were actually equal to the measured gas pressure drop across the scrubber with the equipment under test. No appreciable part of the gas pressure drop resulted from kinetic energy changes alone or from "ineffective friction loss" through dry equipment. No significant energy was supplied from the liquid stream.

The same general behavior appeared during tests of Aerosol E (Figure 21 and Table 5). In all these tests the 0.1% ammonium fluorescein solution was prepared by diluting the stock solution with 0.3N ammonium hydroxide solution, since the potential problems associated with the practice had not been recognized. However, no substantial problems appeared with Aerosol E. The single triangular data point in Figure 21 represents three replicate tests, OS-E-2, OS-E-4, and OS-E-5.

The performance tests of the orifice scrubber with Aerosol F (Figure 22 and Table 6) were completed before the sample analyses and data analysis could be finished. Once the scatter in the data was noted and the SEM observations demonstrated the nonspherical shape of the particles, the studies described above revealed the contamination problem. The new Aerosol G was then developed and tested.

In Figure 22, the performance curve for Aerosol F was drawn as a single straight line, since the precision of the data justified nothing more elaborate. It is possible that the actual curve should have been two-branched as are the curves for the other three aerosols.

The performance curve for Aerosol G (Figure 23 and Table 7) took the same characteristic form as those for the larger Aerosols D and E. During the first four tests (see Table 7), a restriction was inadvertently left in the water inlet, so that water was injected as a jet under substantial upstream water pressures. The equivalent liquid-phase contacting power was calculated, expressed in units of effective friction loss (cm WC), and added to the effective friction loss corresponding to the gas pressure drop. This procedure did improve the correlation of the data. The four data points are shown as triangles in Figure 23. Not only was the precision of the data for Aerosol G much better than that for Aerosol F, but the range of collection efficiencies (or transfer units) was strikingly

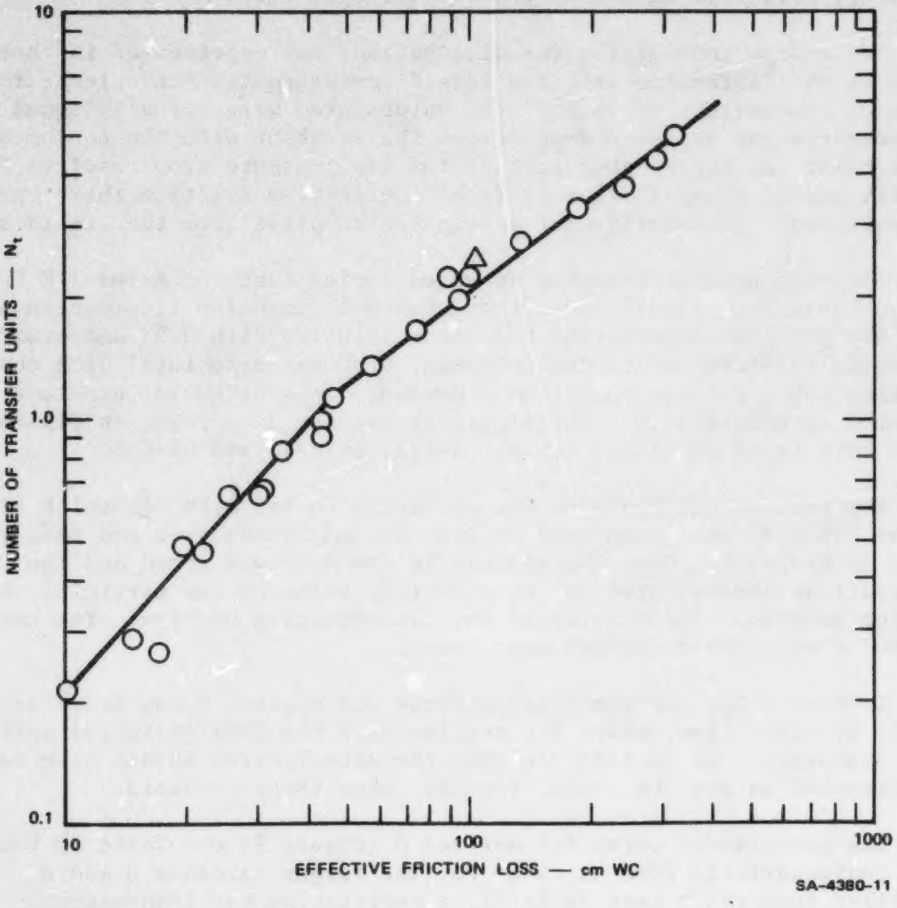

FIGURE 21 ORIFICE SCRUBBER PERFORMANCE CURVE FOR AEROSOL E

TABLE 5. PERFORMANCE OF ORIFICE SCRUBBER ON AEROSOL E

Test code	Contactor orifice size (cm)	Gas flow rate (std m^3/min)	Gas velocity in orifice (m/sec)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								In	Out		
OS-E											
1	2.54	2.263	74.45	1.672	92.65	2.524	1.623	0.7172	0.07887	89.00	2.208
2		2.384	78.42	1.588	103.9	2.830	1.598	0.6701	0.05972	91.09	2.418
3		2.405	79.10	1.574	101.6	2.764	0.8966	0.3729	0.03943	89.42	2.247
4		2.379	78.25	1.591	103.6	2.823	1.498	0.6298	0.05645	91.04	2.412
5		2.370	77.96	1.597	103.6	2.823	1.486	0.6268	0.05418	91.36	2.448
6		2.309	75.93	1.640	92.79	2.528	1.747	0.7567	0.1044	86.20	1.981
7		2.309	75.93	6.558	188.0	5.122	1.186	0.5138	0.01834	96.43	3.333
8		1.991	65.48	7.605	136.1	3.708	1.270	0.6380	0.0417	93.46	2.728
9		1.087	35.74	50.64	291.0	7.926	1.287	1.185	0.01428	98.79	4.418
10		1.145	37.65	39.58	240.8	6.561	1.090	0.9519	0.02209	97.68	3.763
11		0.9359	30.78	69.16	324.8	8.848	1.218	1.301	0.008577	99.34	5.022
12		1.736	57.09	4.362	74.23	2.022	1.423	0.8201	0.1580	80.73	1.647
13		1.554	51.13	4.870	57.84	1.576	1.537	0.9886	0.2516	74.55	1.368
14		1.412	46.44	5.361	46.06	1.255	1.625	1.151	0.3648	68.31	1.149
15		1.319	43.37	5.741	43.10	1.174	1.520	1.153	0.4173	63.80	1.016
16		1.335	43.90	5.672	43.66	1.189	0.8188	0.6135	0.2369	61.39	0.9516
17		1.173	38.57	6.455	35.34	0.9627	1.366	1.164	0.5027	56.83	0.840
18		0.9378	30.85	8.072	25.86	0.7044	1.565	1.669	0.8692	47.93	0.6525
19		0.9924	32.64	3.814	19.70	0.5365	1.564	1.576	0.9790	37.88	0.4762
20	3.81	1.478	21.61	10.24	14.57	0.3968	1.372	0.9280	0.6959	25.01	0.2878
21		2.305	33.70	6.568	30.39	0.8277	1.309	0.5678	0.2962	47.84	0.6509
23		1.832	26.78	3.100	10.17	0.2771	1.843	1.006	0.8091	19.58	0.2179
24		2.228	32.58	3.397	17.07	0.4649	1.528	0.6855	0.5234	23.65	0.2698
25		2.903	42.44	2.608	21.46	0.5847	1.642	0.5655	0.3518	37.80	0.4748
26		2.977	43.52	2.543	30.60	0.8336	1.453	0.4881	0.2516	48.45	0.6626

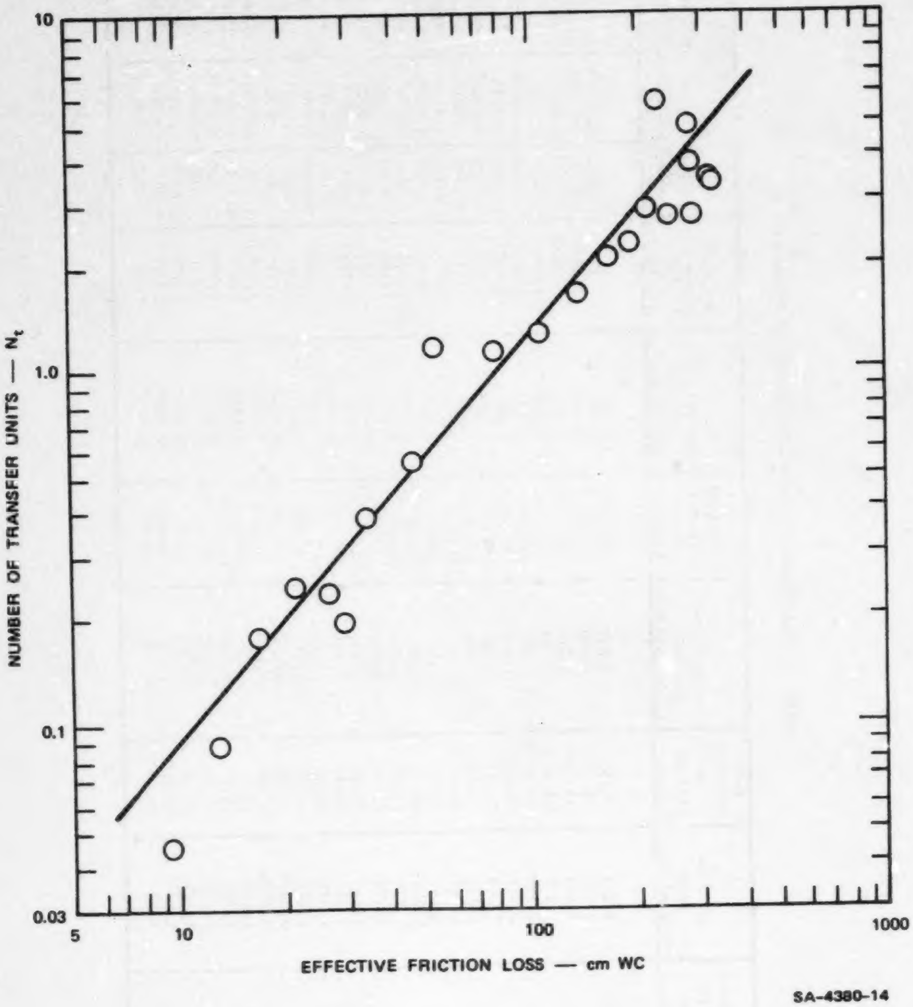

FIGURE 22 ORIFICE SCRUBBER PERFORMANCE CURVE FOR AEROSOL F

TABLE 6. PERFORMANCE OF ORIFICE SCRUBBER ON AEROSOL F

Test code	Contactor orifice size (cm)	Gas flow rate (std m^3/min)	Gas velocity in orifice (m/sec)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								In	Out		
OS-F											
1	2.54	0.9359	30.78	69.16	320.4	8.727	0.1407	0.1503	0.004345	97.11	3.544
3		0.8361	27.50	77.41	283.1	7.712	0.1275	0.1525	0.001155	99.24	4.883
4		0.6681	21.98	96.87	233.7	6.365	0.1305	0.1954	0.0006657	99.66	5.682
5		0.6327	20.81	102.3	216.2	5.889	0.1400	0.2213	0.01223	94.47	2.896
6		1.382	45.44	23.42	186.0	5.066	0.08994	0.0651	0.006563	89.92	2.295
7		1.217	40.05	26.58	165.3	4.502	0.09042	0.07427	0.009002	87.88	2.110
8		1.033	33.99	31.31	135.5	3.690	0.09715	0.0940	0.01749	81.39	1.681
9		0.8775	28.86	36.88	104.7	2.852	0.1073	0.1223	0.03376	72.40	1.287
10		0.6542	21.52	49.47	79.92	2.117	0.1109	0.1695	0.0557	67.14	1.113
11		0.4359	14.34	74.24	53.51	1.458	0.1332	0.3055	0.09551	68.74	1.163
12	3.81	2.763	40.39	5.48	45.94	1.252	0.1213	0.04391	0.02515	42.71	0.5571
13		2.396	35.03	6.318	34.57	0.9416	0.1320	0.05509	0.03764	31.69	0.3811
14		2.379	34.78	6.364	34.57	0.9416	0.1290	0.05424	0.03697	31.84	0.3833
15		1.499	21.92	10.10	29.83	0.8124	0.1110	0.07403	0.06083	17.84	0.1965
16		2.122	31.02	7.135	25.95	0.7068	0.1749	0.08245	0.06459	21.67	0.2442
17		1.850	27.04	8.185	21.72	0.5917	0.1688	0.09126	0.07111	22.08	0.2495
18		1.850	27.04	6.139	17.24	0.4696	0.1611	0.08707	0.07291	16.26	0.1775
19		1.894	27.69	3.996	12.93	0.3522	0.1510	0.07972	0.07291	8.543	0.0893
20		1.894	27.69	1.998	9.396	0.2559	0.1471	0.07764	0.07414	4.511	0.04616
22	2.54	0.7922	26.06	81.70	271.3	7.391	0.1275	0.1610	0.009246	94.26	2.857
23		0.6750	22.20	95.89	242.5	6.605	0.1279	0.1896	0.01135	94.01	2.816
24		0.9359	30.78	69.16	311.0	8.472	0.1705	0.1822	0.004671	97.44	3.664
25		0.8254	27.15	78.42	284.5	7.749	0.1412	0.1710	0.003451	97.98	3.903

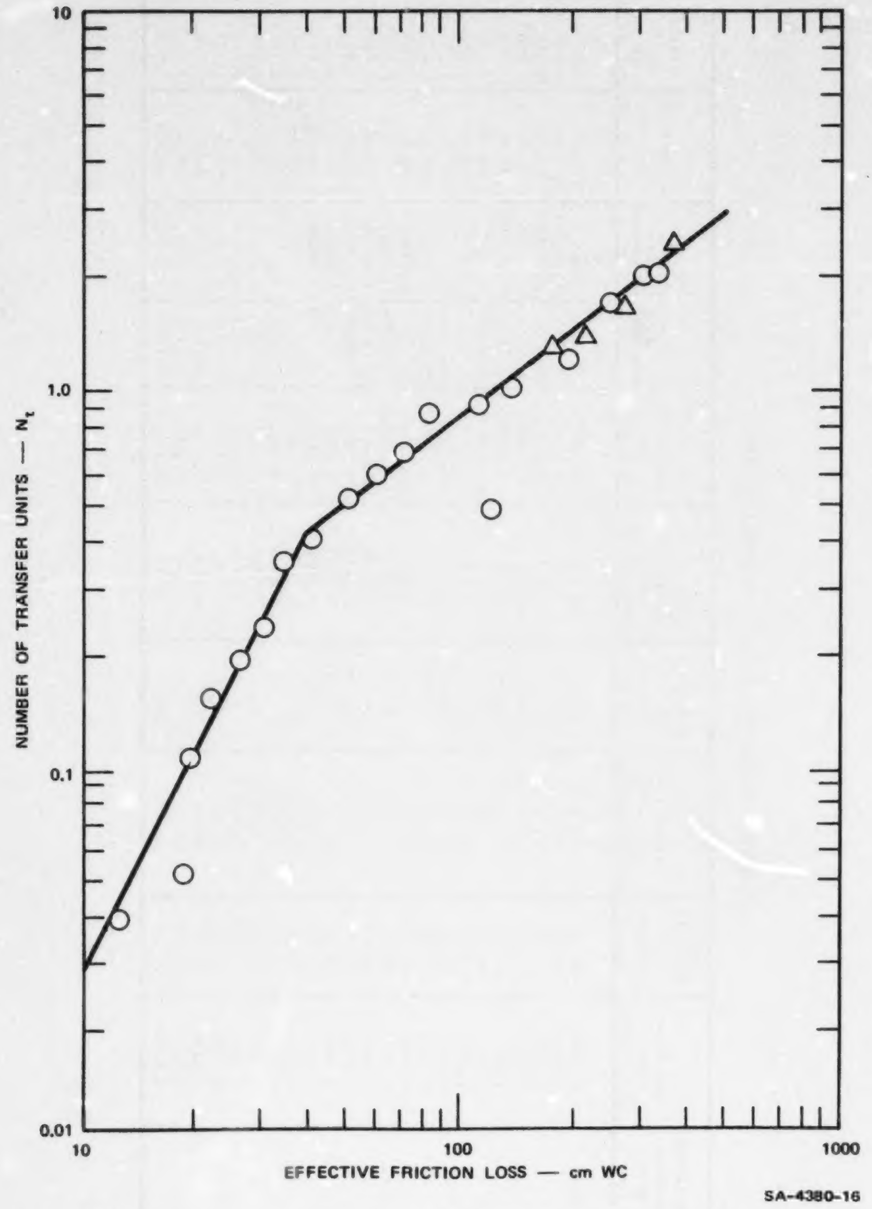

FIGURE 23 ORIFICE SCRUBBER PERFORMANCE CURVE FOR AEROSOL G

TABLE 7. PERFORMANCE OF ORIFICE SCRUBBER ON AEROSOL G

Test code	Contactor orifice size (cm)	Gas flow rate (std m^3/min)	Gas velocity in orifice (m/sec)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								In	Out		
OS-G											
1	2.54	0.9359	30.78	69.16	317.8 359.1*	9.783	0.1076	0.1150	0.009631	91.63	2.480
2		1.442	47.42	26.94	253.3 260.0*	7.055	0.06928	0.04806	0.009007	81.26	1.674
3		1.217	40.05	31.90	201.8 208.5*	5.680	0.06299	0.05174	0.01270	75.46	1.405
4		1.004	33.01	38.70	163.9 172.1*	4.688	0.06782	0.06758	0.01823	73.03	1.310
5		1.721	56.61	8.797	119.2	3.247	0.07753	0.04505	0.02759	38.76	0.4903
6		1.350	44.42	11.21	81.28	2.214	0.08295	0.06142	0.02572	58.12	0.8704
7		0.8571	28.19	17.66	39.96	1.089	0.1121	0.1308	0.08709	33.40	0.4064
8		1.106	36.39	6.842	33.88	0.9228	0.1080	0.09759	0.06837	29.94	0.3558
9		1.185	38.99	3.193	25.77	0.7021	0.1023	0.08629	0.07102	17.70	0.1948
10		1.102	36.26	3.433	21.55	0.5870	0.1009	0.09156	0.07839	14.38	0.1552
11		1.106	36.39	1.711	18.62	0.5072	0.09813	0.08869	0.08416	5.11	0.05246
12	3.81	2.245	32.82	1.686	12.59	0.3428	0.1038	0.04623	0.04444	3.867	0.03943
13		1.883	27.53	2.010	9.31	0.2536	0.1013	0.05376	0.05352	0.449	0.00450
14	2.54	0.9169	30.16	70.59	321.7	8.764	0.08095	0.08829	0.01108	87.45	2.075
15		0.8875	29.19	72.92	298.0	8.118	0.08072	0.09094	0.01194	86.87	2.030
16		1.004	33.01	51.60	243.8	6.642	0.06721	0.06697	0.01220	81.79	1.703
17		1.366	44.93	23.69	188.6	5.136	0.04397	0.03218	0.009470	70.58	1.223
18		1.050	34.54	30.82	133.2	3.627	0.05430	0.0517	0.01837	64.47	1.035
19		1.646	54.15	9.196	110.3	3.004	0.05838	0.03546	0.01397	60.06	0.9314
20		1.269	41.74	11.93	69.76	1.900	0.06730	0.05303	0.02667	49.71	0.6874
21		1.145	37.65	13.23	59.33	1.616	0.06838	0.05974	0.0327	45.27	0.6027
22		1.025	33.72	14.77	49.91	1.360	0.07013	0.06842	0.04050	40.81	0.5245
23		1.012	33.29	3.739	19.22	0.5236	0.07248	0.07161	0.06426	10.27	0.1084
24		1.286	42.29	2.944	29.74	0.8101	0.07473	0.05811	0.04574	21.29	0.2393

*Includes effective friction loss equivalent to contacting power of liquid stream.

different from that for Aerosol F. In fact, the nominal particle sizes of the two aerosols should have been essentially the same. The two solutions contained the same concentration of ammonium fluorescein, and presumably the sizes of the droplets produced in the nebulizer should have been the same or nearly so. The presence of the silica in Aerosol F should not have significantly changed the particle size, although it certainly did affect the shape.

The orifice scrubber performance curves for the four aerosols are summarized together without data points in Figure 24. They may be compared with the corresponding aerosol signature curves of Figure 19, which qualitatively show the same general trends. The deviations between the signature curves for the different aerosols are relatively greater than those between the corresponding orifice scrubber performance curves, demonstrating the greater sensitivity of the miniscrubber to changes in the aerosol.

MULTIPLE-ORIFICE SERIES SCRUBBER

Once the performance of the orifice scrubber was established as a baseline, testing of the multiple-orifice series contactor was undertaken. The data for the tests on Aerosols D, E, and G are given in Tables 8, 9, and 10, respectively. These data have been plotted in Figures 25, 26, and 27; in each figure the corresponding baseline performance curve for the orifice scrubber is shown for reference.

In the tests on Aerosol D (Figure 25), the data for the multiple-orifice series scrubber fitted the upper end of the orifice scrubber performance curve as well as did the original data for the orifice scrubber itself. However, along the lower part of the performance curve, the multiple-orifice scrubber data generally tended to fall below the curve. The significance of this behavior was not obvious from Figure 25 alone. However, the same trend appeared in accentuated degree with Aerosol E (see Figure 26), and was very marked with Aerosol G (Figure 27). With Aerosol G, the performance of the multiple-orifice contactor appeared to attain that of the orifice scrubber only at the lowest and highest ends of the performance range. In Figure 27, a single straight line has been used to represent approximately the performance of the multiple-orifice scrubber; but it appears that, except for the two highest points, the data points would be better fitted by another two-branched curve. From the analogy to the performance curves for Aerosols D and E, one might reasonably expect the performance curves in Figure 27 to merge at the upper ends, but this conjecture could not be confirmed because the limitations of the equipment prevented operation at higher levels of effective friction loss.

SPRAY AND SPRAY-ORIFICE SCRUBBERS

The test data for the spray and spray-orifice scrubbers are presented in Tables 11-19, and in Figures 28-36. Because all the scrubber arrangements used both gas-phase and liquid-phase contacting power, the number of

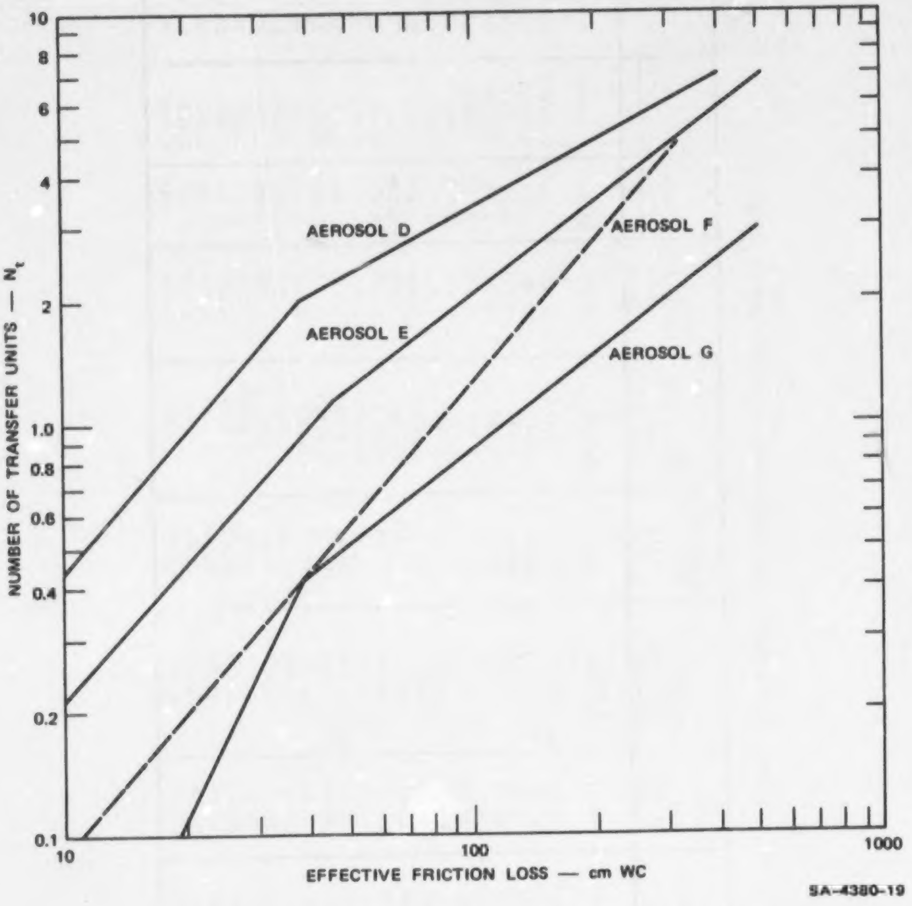

FIGURE 24 SUMMARY OF ORIFICE SCRUBBER PERFORMANCE CURVES FOR AEROSOLS D, E, F, AND G

TABLE 8. PERFORMANCE OF MULTIPLE-ORIFICE SERIES SCRUBBER ON AEROSOL D

Test code	Contactor orifice size (cm)	Gas flow rate (std m^3/min)	Gas velocity in orifice (m/sec)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								In	Out		
MOS-D											
1	3.36 equivalent	0.8361	15.71	77.41	330.5	9.003	16.31	19.51	0.01406	99.93	7.235
2		0.6502	12.22	99.54	281.1	7.657	5.603	8.617	0.02392	99.72	5.887
3		0.5497	10.33	117.7	240.3	6.546	6.094	11.09	0.04428	99.60	5.523
4		0.2651	4.981	244.2	188.4	5.133	4.231	15.96	0.1245	99.22	4.853
5		1.133	21.29	28.56	157.1	4.280	5.391	4.757	0.05589	98.83	4.444
6		0.9776	18.37	33.10	133.0	3.624	4.897	5.009	0.0939	98.13	3.977
7		1.716	32.25	7.543	107.7	2.933	5.046	2.940	0.05532	98.12	3.973
8		1.412	26.53	10.72	83.71	2.280	5.241	3.712	0.1475	96.03	3.225
9		1.025	19.26	14.77	53.51	1.458	5.000	4.878	0.5089	89.57	2.260
10		0.9264	17.41	8.171	27.09	0.7380	5.132	5.540	1.691	76.61	1.453
11		0.9121	17.14	8.300	25.86	0.7044	8.645	9.479	1.726	81.79	1.703
12		1.217	22.88	3.109	34.48	0.9392	5.207	4.277	1.241	70.98	1.237
13		0.9771	18.36	3.874	20.43	0.5565	5.413	5.540	2.690	51.45	0.7226
14		1.114	20.94	3.397	30.17	0.8218	5.156	4.628	1.560	66.29	1.088
15		1.046	19.66	14.47	50.17	1.367	5.397	5.160	0.5227	89.87	2.290
16		1.182	22.21	6.406	43.01	1.172	5.267	4.457	0.6899	84.52	1.866
17		1.137	21.37	6.657	39.65	1.080	5.458	4.800	0.8511	82.27	1.730
18		1.067	20.04	7.452	34.61	0.9428	5.539	5.194	1.121	78.41	1.533
19		0.9816	18.45	8.098	30.43	0.8289	5.409	5.511	1.398	74.63	1.371
20		0.9544	17.94	1.586	20.04	0.5459	5.242	5.492	3.243	40.96	0.5270
21		1.217	22.88	6.218	44.82	1.221	5.183	4.257	0.6667	84.34	1.854
22		1.106	20.79	6.842	36.98	1.007	5.179	4.681	0.9481	79.75	1.597

TABLE 9. PERFORMANCE OF MULTIPLE-ORIFICE SERIES SCRUBBER ON AEROSOL E

Test code	Contactor orifice size (cm)	Gas flow rate (std m^3/min)	Gas velocity in orifice (m/sec)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								In	Out		
MOS-E											
1	3.36 equivalent	0.8307	15.61	77.91	335.9	9.151	1.924	2.316	0.004013	99.83	6.358
2		0.7393	13.89	87.54	312.4	8.509	1.777	2.404	0.009310	99.61	5.554
3		1.210	22.75	37.43	277.7	7.564	1.690	1.396	0.01949	98.60	4.272
4		1.067	20.04	42.48	241.1	6.568	1.652	1.548	0.03072	98.02	3.920
5		1.182	22.21	32.86	215.4	5.867	1.658	1.403	0.04458	96.82	3.449
6		1.319	24.78	24.54	188.3	5.129	1.633	1.238	0.04057	96.72	3.419
7		1.217	22.88	26.58	161.2	4.391	1.672	1.374	0.06667	95.15	3.026
8		0.9359	17.59	34.58	134.1	3.653	1.645	1.758	0.1189	93.24	2.694
9		0.7207	13.54	44.90	105.0	2.860	1.735	2.407	0.2423	89.94	2.296
10		1.382	25.96	10.96	78.57	2.140	1.706	1.235	0.2423	80.38	1.629
11		0.7808	14.67	19.39	34.05	0.9275	1.647	2.110	1.093	48.19	0.6575
12		0.6542	12.29	23.14	25.86	0.7044	1.673	2.558	1.550	39.41	0.5010
13		0.9359	17.59	4.044	20.34	0.5541	1.709	1.826	1.331	27.10	0.3161
14		0.7692	14.46	84.14	320.6	8.734	1.371	1.782	0.006806	99.62	5.568
15		0.7514	14.12	86.13	311.6	8.487	1.569	2.088	0.006388	99.69	5.789
16		1.163	21.86	13.01	65.70	1.790	1.485	1.276	0.3737	70.72	1.228
17		1.046	19.66	14.47	51.72	1.409	1.506	1.440	0.5509	61.74	0.9607
18		0.9452	17.76	16.02	43.06	1.173	1.464	1.549	0.7536	51.35	0.7205
19		1.004	18.86	7.543	30.17	0.8218	1.444	1.439	0.8170	43.23	0.5661
20		0.9590	18.02	3.947	21.64	0.5894	1.463	1.525	1.099	27.96	0.3279

TABLE 10. PERFORMANCE OF MULTIPLE-ORIFICE SERIES SCRUBBER ON AEROSOL G

Test code	Contactor orifice size (cm)	Gas flow rate (std m^3/min)	Gas velocity in orifice (m/sec)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								In	Out		
MOS-G 1	3.36 equivalent	1.025	19.26	63.14	324.3	8.834	0.1589	0.1550	0.01460	90.58	2.362
2		0.7015	13.18	92.26	297.3	8.099	0.1081	0.1541	0.01677	89.12	2.218
3		1.054	19.81	42.97	243.6	6.634	0.09769	0.09266	0.02202	76.24	1.437
4		1.442	27.09	22.45	214.0	5.830	0.08944	0.06204	0.01664	73.18	1.316
5		1.319	24.78	24.54	189.6	5.166	0.08766	0.06648	0.02267	65.91	1.076
6		1.145	21.51	28.27	162.6	4.428	0.08306	0.07255	0.02851	60.70	0.9341
8		1.838	34.55	8.235	132.1	3.598	0.0804	0.04373	0.01809	58.65	0.8831
9		1.634	30.70	9.268	106.5	2.900	0.08116	0.04968	0.02397	51.75	0.7288
10		1.252	23.53	12.09	67.32	1.834	0.08824	0.07047	0.04553	35.39	0.4368
11		1.067	20.04	14.20	55.54	1.513	0.08342	0.07821	0.05397	31.00	0.3710
12		1.269	23.85	5.965	49.56	1.350	0.08025	0.06324	0.04652	26.43	0.3069
13		1.122	21.08	6.747	38.79	1.057	0.07837	0.06985	0.05532	20.81	0.2333
14		0.9948	18.69	7.609	30.17	0.8218	0.07846	0.07886	0.06532	17.18	0.1885
15		0.9816	18.45	3.856	24.14	0.6575	0.07429	0.07568	0.06730	11.07	0.1173
16		0.9359	17.59	2.022	19.96	0.5436	0.07550	0.08068	0.07340	9.01	0.0945

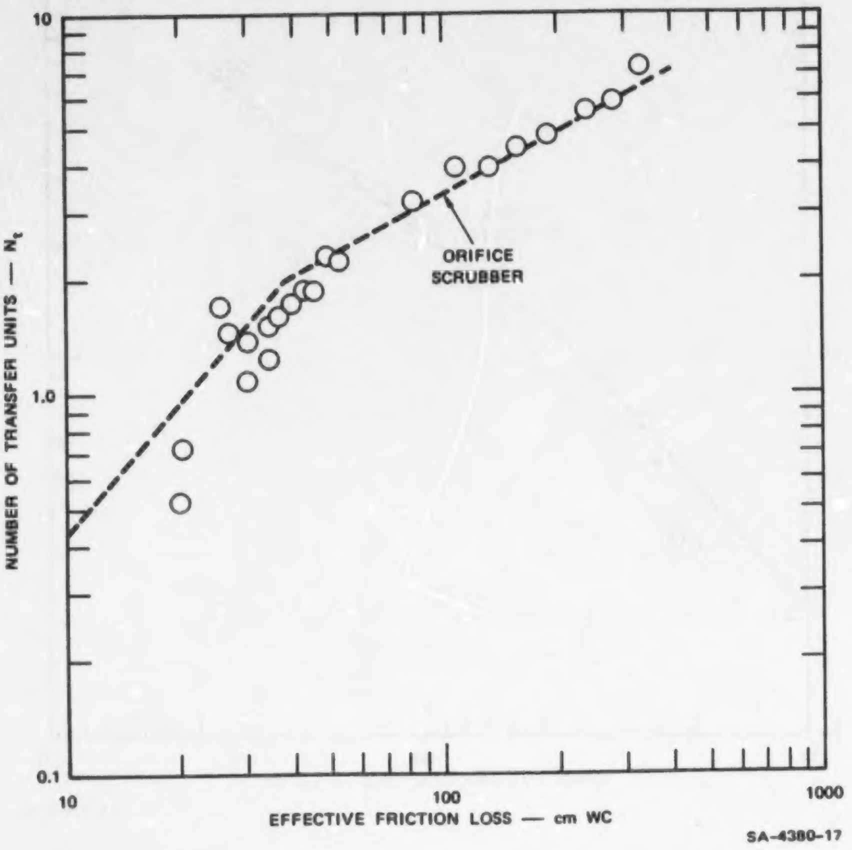

FIGURE 25 MULTIPLE-ORIFICE SERIES SCRUBBER PERFORMANCE ON AEROSOL D

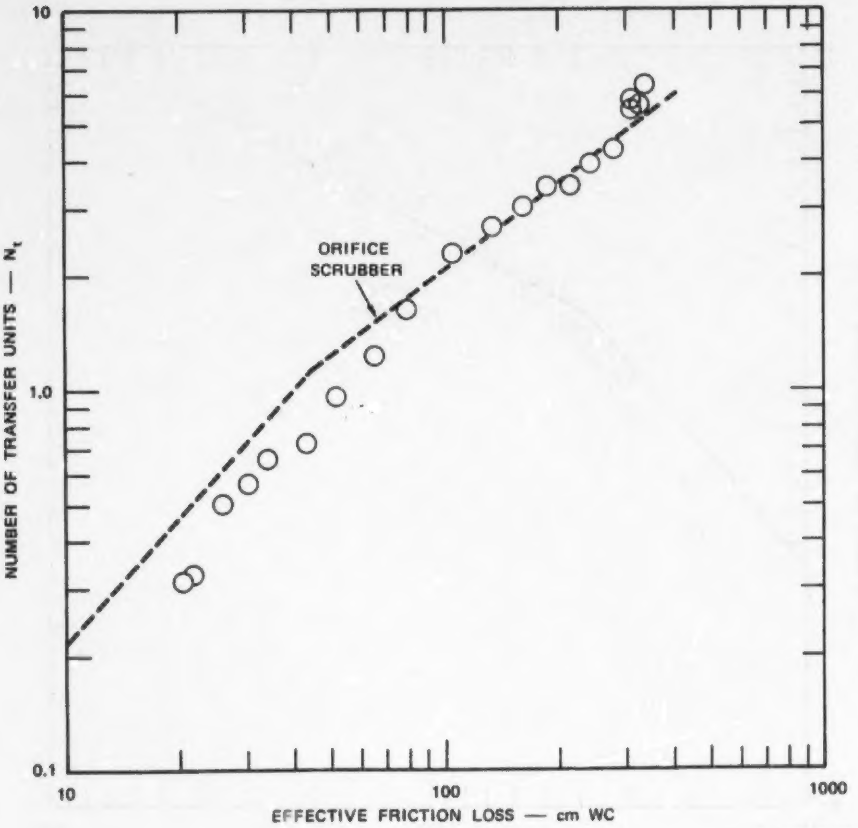

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FIGURE 26 MULTIPLE-ORIFICE SERIES SCRUBBER PERFORMANCE ON AEROSOL E

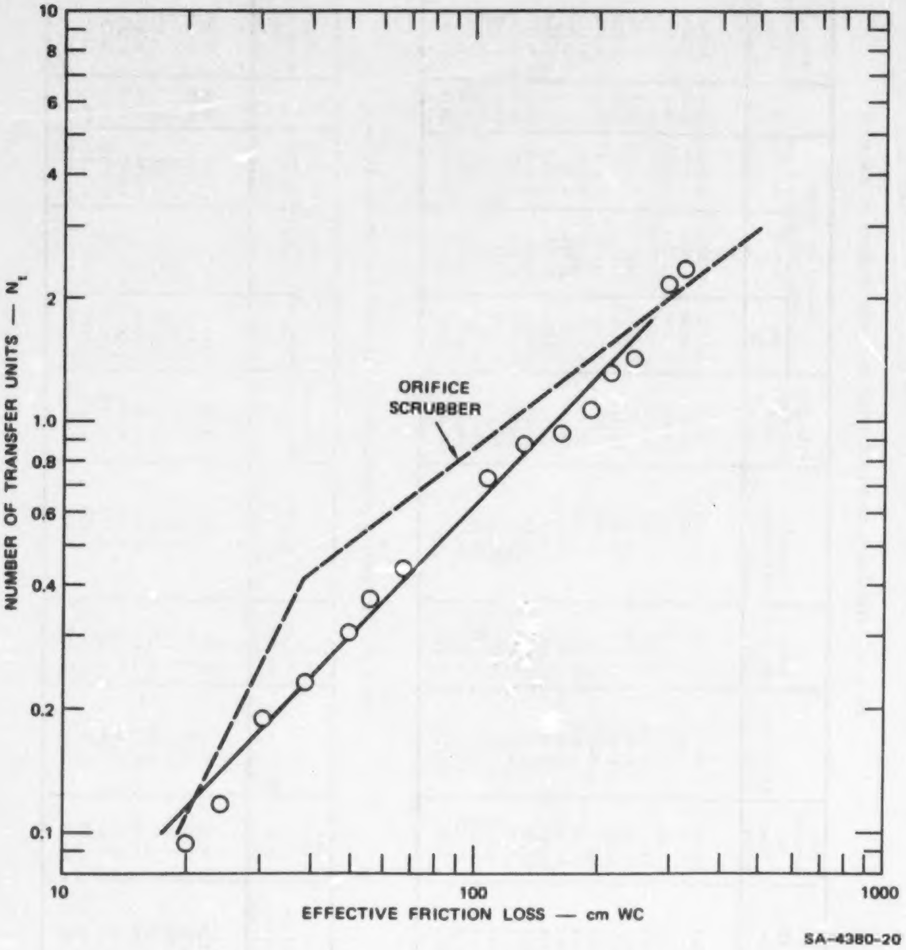

FIGURE 27 MULTIPLE-ORIFICE SERIES SCRUBBER PERFORMANCE ON AEROSOL G

TABLE 11. PERFORMANCE OF CONFIGURATION SS1 SPRAY SCRUBBER ON AEROSOL D

Test code	Contactor line size (cm)	Gas flow rate (std m^3/min)	Gas velocity in line (m/sec)	Water rate (liter/min)	Water pressure (atm)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)			% P_L	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								Gas P_G	Liquid P_L	Total P_T			In	Out		
SS1-D																
1	5.842	4.571	28.42	8.516	5.511	1.863	26.55	0.7232	0.2891	1.012	28.6	5.946	1.301	0.3075	76.36	1.442
2		4.172	25.94	8.327	5.477	1.996	22.24	0.6058	0.3078	0.9136	33.7	5.601	1.342	0.3660	72.74	1.300
3		3.833	23.83	8.138	5.443	2.123	19.01	0.5178	0.3254	0.8431	38.6	5.685	1.483	0.4791	67.70	1.130
4		4.383	27.25	5.299	2.347	1.209	16.46	0.4485	0.07991	0.5284	15.1	5.434	1.240	0.4548	63.33	1.003
5		2.430	15.11	3.785	0.8505	1.557	3.62	0.09862	0.03729	0.1359	27.4	5.559	2.287	1.957	14.42	0.1558
6		4.597	28.58	9.955	13.74	2.165	27.50	0.7491	0.8379	1.587	52.8	5.983	1.301	0.2287	82.42	1.739
7		2.011	12.51	9.652	13.61	4.798	7.456	0.2031	1.838	2.041	90.1	5.645	2.806	1.254	55.31	0.8054
8		2.072	12.89	8.478	10.21	4.091	6.724	0.1832	1.175	1.359	86.5	5.713	2.757	1.385	49.76	0.6883
9		3.922	24.38	39.48	10.07	10.07	72.20	1.967	2.854	4.821	59.2	5.778	1.473	0.05078	96.55	3.368
10		3.214	19.99	39.48	10.07	12.28	54.32	1.480	3.482	4.961	70.2	6.149	1.913	0.1052	94.50	2.900
11		1.894	11.78	39.48	10.07	20.84	30.00	0.8171	5.908	6.725	87.9	6.100	3.220	0.2962	90.80	2.386
12		1.217	7.57	39.48	10.07	32.43	21.55	0.5870	9.192	9.779	94.0	6.036	4.958	0.4530	90.86	2.393
13		1.025	6.373	39.48	10.07	38.51	19.57	0.5330	10.92	11.45	95.4	6.063	5.915	0.4661	92.12	2.541
14		1.145	7.118	35.92	8.505	31.38	18.19	0.4954	7.513	8.009	93.8	5.825	5.088	0.6272	87.67	2.093
15		1.436	8.927	27.18	4.763	18.93	14.91	0.4062	2.539	2.945	86.2	5.625	3.918	1.092	72.12	1.277
16		1.980	12.31	15.14	1.225	7.646	8.017	0.2184	0.2636	0.4820	54.7	5.783	2.920	1.840	37.00	0.4621

TABLE 12. PERFORMANCE OF CONFIGURATION SS2 SPRAY SCRUBBER ON AEROSOL D

Test code	Contactor line size (cm)	Gas flow rate (std m^3/min)	Gas velocity in line (m/sec)	Water rate (liter/min)	Water pressure (atm)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)			% P_L	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								Gas P_G	Liquid P_L	Total P_T			In	Out		
SS2-D																
1	5.842	1.350	8.397	22.67	12.25	16.79	16.81	0.4579	5.789	6.246	92.7	5.689	4.212	0.5121	87.84	2.107
2		1.757	10.93	15.22	5.171	8.659	11.21	0.3053	1.261	1.566	80.5	5.874	3.343	1.092	67.33	1.119
3		1.350	8.397	22.97	12.11	17.01	16.81	0.4579	5.801	6.259	92.7	5.719	4.235	0.5200	87.72	2.097
4		1.757	10.93	15.22	5.171	8.659	11.21	0.3053	1.261	1.566	80.5	5.525	3.144	1.092	65.26	1.057
5		1.286	7.995	24.26	13.61	18.87	17.24	0.4696	7.229	7.698	93.9	5.531	4.301	0.3989	90.73	2.378
6		1.861	11.57	12.94	3.946	6.956	9.827	0.2677	0.7728	1.040	74.3	4.939	2.654	1.127	57.54	0.8567
7		1.910	11.87	11.96	2.926	6.263	9.094	0.2477	0.5159	0.7636	67.6	5.395	2.825	1.283	54.59	0.7895
8		1.959	12.18	11.54	2.705	5.893	8.404	0.2289	0.4487	0.6776	66.2	5.515	2.815	1.369	51.35	0.7206
9		2.291	14.24	3.785	0.1021	1.652	3.965	0.1080	0.00475	0.1128	4.2	9.341	4.078	2.028	50.27	0.6985

TABLE 13. PERFORMANCE OF CONFIGURATION SS3 SPRAY SCRUBBER ON AEROSOL D

Test code	Contactor line size (cm)	Gas flow rate (std m^3/min)	Gas velocity in line (m/sec)	Water rate (liter/min)	Water pressure (atm)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)			% P_L	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								Gas P_G	Liquid P_L	Total P_T			In	Out		
SS3-D																
1	5.842	2.413	15.01	19.42	11.98	8.046	2.370	0.06457	2.712	2.777	97.7	5.254	2.177	0.5546	74.53	1.367
2		2.437	15.15	17.98	9.798	7.377	3.060	0.08336	2.035	2.118	96.1	5.657	2.321	0.7887	66.02	1.079
3		2.305	14.33	16.50	7.485	7.160	3.879	0.1057	1.509	1.614	93.5	5.399	2.343	1.031	55.97	0.8202
4		2.236	13.90	13.93	5.273	6.230	4.741	0.1291	0.9248	1.054	87.7	5.292	2.367	1.378	41.78	0.5409
5		2.170	13.49	11.35	2.211	5.233	5.344	0.1456	0.3257	0.4713	69.1	5.498	2.533	1.716	32.27	0.3896
6		2.300	14.30	3.785	0.0510	1.646	3.879	0.1057	0.002365	0.108	2.2	5.476	2.381	0.7245	69.58	1.190
7		2.447	15.22	21.04	13.61	8.599	1.638	0.04461	3.294	3.339	98.7	5.315	2.172	0.4182	80.75	1.647
8		4.676	29.07	20.70	13.61	4.428	24.14	0.6575	1.696	2.354	72.0	5.623	1.203	0.1881	84.36	1.855
9		4.334	26.95	20.70	13.61	4.777	20.17	0.5495	1.830	2.379	76.9	5.449	1.257	0.2440	80.60	1.640
10		3.973	24.70	20.70	13.61	5.211	15.86	0.4320	1.996	2.428	82.2	5.706	1.436	0.3135	78.17	1.522
11		3.563	22.15	20.70	13.61	5.811	11.03	0.3006	2.226	2.527	88.1	5.568	1.563	0.3790	75.74	1.417
12		2.900	18.03	20.70	13.61	7.139	5.258	0.1432	2.735	2.878	95.0	5.610	1.934	0.4511	76.68	1.456
13		4.693	29.18	15.22	6.804	3.242	25.86	0.7044	0.6211	1.325	46.9	5.527	1.178	0.2235	81.02	1.662
14		4.292	26.69	15.22	6.804	3.545	21.55	0.5870	0.6791	1.266	53.6	5.805	1.353	0.3135	76.82	1.462
15		3.882	24.14	15.22	6.804	3.920	17.24	0.4696	0.7508	1.220	61.5	5.744	1.480	0.4287	71.03	1.239
16		3.333	20.72	15.22	6.804	4.565	12.07	0.3287	0.8745	1.203	72.7	5.921	1.777	0.5722	67.79	1.133
17		2.879	17.90	15.22	6.804	5.285	8.62	0.2348	1.012	1.247	81.2	5.639	1.959	0.8494	56.63	0.8355
18		2.282	14.19	15.22	6.804	6.669	4.396	0.1198	1.277	1.397	91.4	5.659	2.480	1.228	50.48	0.7029

TABLE 14. PERFORMANCE OF CONFIGURATION SS4 SPRAY SCRUBBER ON AEROSOL D

Test code	Contactor line size (cm)	Gas flow rate (std m^3/min)	Gas velocity in line (m/sec)	Water rate (liter/min)	Water pressure (atm)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)			% P_L	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								Gas P_G	Liquid P_L	Total P_T			In	Out		
SS4-D																
1	5.842	4.417	27.47	17.79	13.61	4.027	41.29	1.125	1.543	2.668	57.8	5.239	1.186	0.1674	85.89	1.958
2		3.790	23.56	17.49	13.61	4.614	30.08	0.8195	1.768	2.587	68.3	5.442	1.436	0.2874	79.99	1.609
3		3.045	18.93	17.34	13.61	5.694	21.55	0.5870	2.181	2.768	78.8	5.392	1.771	0.5115	71.12	1.242
4		2.578	16.03	17.34	13.61	6.724	17.15	0.4673	2.576	3.043	84.6	5.341	2.072	0.7452	64.02	1.022
5		2.217	13.79	17.34	13.61	7.818	13.88	0.3780	2.995	3.373	88.8	5.152	2.323	0.9620	58.60	0.8818
6		1.792	11.15	17.34	13.61	9.671	10.69	0.2912	3.705	3.996	92.7	5.401	3.013	1.352	55.13	0.8014
7		4.557	28.34	13.25	6.804	2.907	32.67	0.8899	0.5568	1.447	38.5	4.921	1.080	0.2026	81.24	1.674
8		4.006	24.91	13.25	6.804	3.307	25.77	0.7021	0.6335	1.336	47.4	5.020	1.253	0.3311	73.58	1.331
9		3.595	22.35	13.25	6.804	3.685	21.12	0.5753	0.7059	1.281	55.1	5.082	1.414	0.4593	67.51	1.124
10		3.157	19.63	13.25	6.804	4.197	17.15	0.4673	0.8039	1.271	63.2	5.289	1.676	0.6414	61.72	0.9602
11		2.562	15.93	13.25	6.804	5.170	12.67	0.3452	0.9904	1.336	74.2	5.287	2.063	0.9881	52.12	0.7364
12		1.984	12.34	13.25	6.804	6.676	8.448	0.2301	1.279	1.509	84.8	5.406	2.724	1.456	46.55	0.6264
13		1.286	7.995	17.15	13.61	13.33	6.896	0.1878	5.109	5.296	96.5	5.219	4.059	2.080	48.75	0.6685
14		1.485	9.233	15.06	10.21	10.14	6.896	0.1878	2.915	3.103	94.0	5.506	3.708	2.081	43.87	0.5775
15		1.286	7.995	15.06	10.21	11.72	6.034	0.1644	3.366	3.531	95.3	5.243	4.078	2.418	40.70	0.5225
16		1.286	7.995	12.68	6.804	9.861	4.827	0.1315	1.889	2.020	93.5	5.411	4.208	2.912	30.80	0.3682
17		1.286	7.995	9.463	3.402	7.359	3.465	0.09439	0.7048	0.7992	88.2	5.423	4.218	3.473	17.67	0.1944
18		1.286	7.995	7.570	1.701	5.887	2.931	0.07983	0.2819	0.3618	77.9	5.492	4.271	3.796	11.12	0.1179
19		3.540	22.01	17.34	13.61	4.897	25.95	0.7068	1.876	2.583	72.6	5.248	1.482	0.3605	75.68	1.414
20		3.540	22.01	15.22	10.21	4.298	23.02	0.6269	1.235	1.862	66.3	5.332	1.506	0.4389	70.86	1.233
21		3.540	22.01	12.60	6.804	3.560	20.34	0.5541	0.6820	1.236	55.2	5.138	1.451	0.5117	64.74	1.042
22		3.540	22.01	9.463	3.402	2.673	16.55	0.4508	0.2560	0.7068	36.2	5.684	1.606	0.6166	61.60	0.9570
23		3.540	22.01	7.570	1.905	2.138	14.40	0.3921	0.1147	0.5068	22.6	5.326	1.505	0.6717	55.35	0.8064
24		2.610	16.23	18.36	13.61	7.034	17.15	0.4673	2.695	3.162	85.2	4.898	1.877	0.6901	63.23	1.000
25		2.610	16.23	15.22	10.14	5.830	14.65	0.3992	1.664	2.063	80.7	5.174	1.982	0.8651	56.36	0.8293
26		2.610	16.23	12.60	6.804	4.829	12.15	0.3311	0.9250	1.256	73.6	5.042	1.932	0.9756	49.49	0.6831
27		2.610	16.23	11.13	4.933	4.264	11.29	0.3076	0.5921	0.8997	65.8	5.150	1.973	1.075	45.53	0.6075
28		2.610	16.23	9.463	3.266	3.626	10.26	0.2794	0.3333	0.6128	54.4	4.978	1.907	1.148	39.83	0.5080
29		2.610	16.23	7.570	1.701	2.900	8.448	0.2301	0.1389	0.3690	37.6	5.090	1.950	1.295	33.6	0.4096
*30		0.7207	4.481	17.34	13.54	24.05	4.138	0.1127	9.169	9.281	98.8	13.28	18.42	6.273	65.95	1.077
*31		0.7207	4.481	15.22	10.21	21.11	3.362	0.09158	6.066	6.158	98.5	13.91	19.31	7.948	58.83	0.8875
*32		0.7207	4.481	12.68	6.804	17.59	2.629	0.07162	3.370	3.442	97.9	13.49	18.72	10.56	43.62	0.5730
*33		0.7207	4.481	9.463	3.266	13.13	1.983	0.0540	1.207	1.261	95.7	13.40	18.60	13.29	28.53	0.3359
*34		0.7207	4.481	7.570	1.837	10.50	1.681	0.0458	0.5432	0.5890	92.2	13.37	18.55	15.83	14.65	0.1585
*35		1.872	11.64	7.570	1.769	4.043	4.569	0.1244	0.2014	0.3258	61.8	15.52	8.292	5.982	27.86	0.3266
36		2.763	17.18	7.191	1.701	2.603	9.223	0.2512	0.1247	0.3759	33.2	4.390	1.589	1.004	36.78	0.4586
37		4.074	25.33	7.570	1.769	1.858	19.83	0.5401	0.09254	0.6326	14.6	4.739	1.163	0.4048	65.20	1.056
38		4.650	28.91	7.381	1.701	1.587	26.03	0.7091	0.07602	0.7851	9.7	4.821	1.037	0.2514	75.76	1.417
39		4.641	28.86	9.463	3.334	2.039	28.70	0.7819	0.1914	0.9733	19.7	4.628	0.9972	0.2218	77.75	1.503
40		4.074	25.33	9.463	3.266	2.323	22.07	0.6011	0.2136	0.8147	26.2	4.572	1.122	0.3429	69.45	1.186
41		2.763	17.18	9.463	3.334	3.425	10.77	0.2935	0.3215	0.6150	52.3	4.245	1.537	0.9072	40.96	0.5270
42		1.872	11.64	9.463	3.402	5.054	5.862	0.1597	0.4841	0.6438	75.2	4.534	2.422	1.795	25.90	0.2997
43		0.7207	4.481	17.34	13.61	24.05	4.138	0.1127	9.215	9.328	98.8	4.841	6.716	2.570	61.74	0.9608
44		0.7207	4.481	15.22	10.21	21.11	3.405	0.09275	6.066	6.159	98.5	4.124	5.722	2.888	49.54	0.6839
45		0.7207	4.481	12.76	6.804	17.70	2.586	0.07044	3.390	3.461	98.0	4.835	6.709	4.228	36.98	0.4617
46		0.7207	4.481	9.463	3.334	13.13	2.043	0.05565	1.232	1.288	95.7	4.380	6.077	4.919	19.06	0.2114
47		0.7207	4.481	7.570	1.769	10.50	1.595	0.04344	0.5231	0.5666	92.3	4.301	5.968	5.550	6.998	0.0726
48		1.872	11.64	7.267	1.701	3.882	4.569	0.1244	0.1859	0.3103	59.9	4.485	2.396	1.963	18.07	0.1994

*Sweep air 6 liters/min.

TABLE 15. PERFORMANCE OF CONFIGURATION SS4 SPRAY SCRUBBER ON AEROSOL G

Test code	Contactor line size (cm)	Gas flow rate (std m^3/min)	Gas velocity in line (m/sec)	Water rate (liter/min)	Water pressure (atm)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)			% P_L	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								Gas P_G	Liquid P_L	Total P_T			In	Out		
SS4-G																
1	5.842	0.7393	4.597	7.570	1.769	10.24	1.638	0.04461	0.5099	0.5546	92.0	0.1171	0.1583	0.1445	8.74	0.0914
2		1.286	7.995	7.570	1.837	5.887	2.931	0.07983	0.3045	0.3843	79.2	0.1191	0.09263	0.09014	2.70	0.0273
3		1.872	11.64	7.381	1.769	3.942	4.569	0.1244	0.1963	0.3208	61.2	0.1770	0.09452	0.06702	29.1	0.3439
4		2.907	18.08	7.381	1.701	2.539	10.09	0.2747	0.1216	0.3963	30.7	0.1141	0.03923	0.03886	0.956	0.0096
5		4.684	29.13	7.267	1.701	1.551	25.00	0.6809	0.07429	0.7552	9.8	0.1223	0.02611	0.02289	12.34	0.1317
6		4.654	28.94	9.463	3.334	2.033	28.45	0.7749	0.1908	0.9657	19.8	0.1184	0.02544	0.02154	15.34	0.1665
7		2.907	18.08	9.463	3.402	3.255	11.98	0.3264	0.3117	0.6381	48.9	0.1084	0.03729	0.03539	5.09	0.0522
8		1.872	11.64	9.652	3.402	5.155	5.689	0.1550	0.4938	0.6487	76.1	0.1007	0.05381	0.05309	1.34	0.0135
9		1.286	7.995	9.841	3.402	7.653	3.189	0.08688	0.7330	0.8199	89.4	0.09582	0.07452	0.07402	0.67	0.0067
10		0.7207	4.481	9.652	3.334	13.39	1.948	0.05307	1.257	1.310	96.0	0.09387	0.1302	0.1225	5.93	0.0612
11		0.7207	4.481	12.76	6.804	17.70	2.672	0.07279	3.390	3.463	97.9	0.09395	0.1304	0.1156	11.33	0.1202
12		1.286	7.995	12.68	6.804	9.861	4.569	0.1244	1.889	2.013	93.8	0.09017	0.07012	0.06702	4.43	0.0453
13		1.872	11.64	12.76	6.804	6.813	7.241	0.1972	1.305	1.502	86.9	0.09151	0.04888	0.04646	4.95	0.0507
14		2.907	18.08	12.68	6.804	4.361	14.05	0.3827	0.8354	1.218	68.6	0.09053	0.03114	0.02914	6.41	0.0662
15		4.571	28.42	12.76	6.804	2.791	32.41	0.8829	0.5346	1.417	37.7	0.1079	0.02361	0.02011	14.85	0.1608
16		4.490	27.92	17.34	13.61	3.861	38.45	1.047	1.479	2.526	58.6	0.09663	0.02152	0.01604	25.47	0.2940
17		2.907	18.08	17.34	13.61	5.963	18.79	0.5119	2.284	2.796	81.7	0.1496	0.05147	0.04300	16.46	0.1799
18		1.872	11.64	17.34	13.61	9.26	10.60	0.2888	3.547	3.836	92.5	0.1463	0.07815	0.06755	13.57	0.1458
19		1.286	7.995	17.34	13.61	13.48	7.499	0.2043	5.165	5.369	96.2	0.1101	0.08562	0.07402	13.54	0.1455
20		0.7207	4.481	17.34	13.61	24.05	4.051	0.1104	9.215	9.325	98.8	0.1048	0.1455	0.1158	20.39	0.2280

TABLE 16. PERFORMANCE OF CONFIGURATION SS5 SPRAY SCRUBBER ON AEROSOL D

Test code	Contactor line size (cm)	Gas flow rate (std m³/min)	Gas velocity in line (m/sec)	Water rate (liter/min)	Water pressure (atm)	Liquid-to-gas ratio (liter/std m³)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m³)			% P_L	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m³)		Collection efficiency (%)	Transfer units (N_t)
								Gas P_G	Liquid P_L	Total P_T			In	Out		
SS5-D																
1	5.842	1.905	11.85	21.80	13.61	11.44	-8.810	-0.24	4.384	4.144	105.8	3.323	1.744	0.1355	92.23	2.555
4		4.606	28.64	21.88	13.61	4.750	13.53	0.3686	1.820	2.188	83.15	4.158	0.9027	0.1668	81.52	1.689
5		4.259	26.48	21.88	13.61	5.137	9.913	0.270	1.968	2.238	87.93	3.944	0.9260	0.1813	80.42	1.631
6		3.642	22.65	21.88	13.61	6.007	4.224	0.1151	2.301	2.416	95.24	3.702	1.016	0.2021	80.11	1.615
7		3.176	19.75	21.88	13.61	6.888	0.3448	0.00939	2.639	2.648	99.65	3.686	1.161	0.2118	81.75	1.701
8		2.710	16.85	21.88	13.61	8.072	3.620	0.0986	3.092	3.191	96.91	3.588	1.324	0.1774	86.60	2.010
9		1.634	10.16	21.88	13.61	13.39	-10.30	-0.2806	5.131	4.850	105.8	3.859	2.362	0.1178	95.01	2.999
10		1.350	8.397	21.88	13.61	16.20	-12.59	-0.3428	6.206	5.863	105.8	3.198	2.368	0.0967	95.92	3.198
11		0.9816	6.103	21.88	13.61	22.29	-15.00	-0.4086	8.539	8.130	105.0	3.052	3.109	0.0949	96.95	3.490
12		1.442	8.964	15.52	6.804	10.76	-3.776	-0.1028	2.062	1.959	105.2	3.953	2.742	0.6102	77.74	1.503
13		1.302	8.097	15.52	6.804	11.92	-4.224	-0.1151	2.283	2.168	105.3	3.114	2.391	0.5178	78.35	1.530
14		0.8875	5.519	15.52	6.804	17.48	-5.818	-0.1585	3.349	3.191	105.0	3.045	3.431	0.4717	86.25	1.984
15		1.217	7.570	13.63	5.103	11.19	-2.758	-0.0751	1.608	1.533	104.9	3.922	3.222	0.9711	69.86	1.199
16		0.9816	6.103	13.25	5.103	13.50	-3.707	-0.1010	1.939	1.838	105.5	3.232	3.293	0.7861	76.12	1.432
17		0.4121	2.562	13.63	5.103	33.07	-5.301	-0.1444	4.751	4.606	103.1	2.748	6.669	0.7398	88.91	2.199
18		2.180	13.55	18.81	10.21	8.631	-5.758	-0.1569	2.480	2.323	106.8	4.126	1.893	0.2681	85.84	1.955
19		1.527	9.495	18.81	10.21	12.32	-7.068	-0.1925	3.540	3.347	105.8	3.877	2.539	0.2413	90.50	2.354
20		0.9816	6.103	18.81	10.21	19.16	-9.999	-0.2724	5.507	5.234	105.2	2.898	2.953	0.1831	93.80	2.780
21		4.268	26.54	21.80	13.61	5.108	10.34	0.2818	1.957	2.239	87.41	3.192	0.7478	0.1554	79.22	1.571
22		3.901	24.25	21.80	13.61	5.589	6.896	0.1878	2.141	2.329	91.93	3.176	0.8143	0.1693	79.21	1.571
23		4.544	28.25	15.86	6.804	3.490	15.52	0.4227	0.6685	1.091	61.27	3.252	0.7157	0.2193	69.36	1.183
24		3.973	24.70	15.86	6.804	3.992	10.52	0.2865	0.7646	1.051	72.75	3.190	0.8029	0.3051	62.00	0.9675
25		3.163	19.67	15.86	6.804	5.014	5.172	0.1409	0.9604	1.101	87.21	3.171	1.002	0.4253	57.57	0.8573
26		2.562	15.93	15.86	6.804	6.189	1.810	0.0493	1.186	1.235	96.01	3.014	1.176	0.4623	60.69	0.9336
27		4.579	28.47	10.67	3.266	2.331	15.43	0.4203	0.2143	0.6346	33.77	3.739	0.8165	0.3145	61.49	0.9542
28		3.848	23.93	11.13	3.402	2.892	10.34	0.2818	0.2769	0.5587	49.57	1.128	0.2931	0.1527	47.90	0.6520
29		3.004	18.68	10.94	3.402	3.641	5.215	0.1421	0.3487	0.4908	71.06	4.081	1.358	0.8322	38.74	0.4900
30		2.314	14.39	11.05	3.402	4.776	2.457	0.0669	0.4575	0.5244	87.24	2.764	1.194	1.104	7.56	0.0786
31		2.309	14.35	11.13	3.402	4.820	2.414	0.0657	0.4617	0.5274	87.53	2.964	1.284	0.8651	32.61	0.3947
32		0.9590	5.963	11.13	3.402	11.60	-1.784	-0.0486	1.111	1.063	104.6	3.010	3.138	1.417	54.84	0.7951
33		0.2901	1.804	11.05	3.402	38.10	-2.974	-0.0810	3.649	3.568	102.3	2.629	9.064	2.186	75.88	1.422

TABLE 17. PERFORMANCE OF CONFIGURATION SS5 SPRAY SCRUBBER ON AEROSOL G

Test code	Contactor line size (cm)	Gas flow rate (std m^3/min)	Gas velocity in line (m/sec)	Water rate (liter/min)	Water pressure (atm)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)			% P_L	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								Gas P_G	Liquid P_L	Total P_T			In	Out		
SS5-G																
1	5.842	2.102	13.07	21.80	13.61	10.37	-7.672	-0.2090	3.973	3.764	105.6	0.1396	0.06641	0.04511	32.08	0.3868
2		1.634	10.16	15.86	6.804	9.709	-2.931	-0.0798	1.860	1.780	104.5	0.1156	0.07077	0.06002	15.20	0.1649
3		0.9816	6.103	9.652	2.041	9.833	-0.8620	-0.0235	0.5651	0.5416	104.3	0.1134	0.1155	0.1145	0.904	0.00908
4		1.634	10.16	21.80	13.61	13.35	-10.86	-0.2959	5.113	4.817	106.1	0.1017	0.06229	0.03953	36.53	0.4546
5		0.9816	6.103	21.76	13.47	22.17	-14.14	-0.3851	8.409	8.024	104.8	0.09706	0.09888	0.05482	44.56	0.5899
6		4.795	29.81	21.80	13.47	4.547	15.60	0.4250	1.724	2.149	80.23	0.09731	0.02029	0.01619	20.23	0.2260
7		4.268	26.54	21.80	13.61	5.108	9.654	0.2630	1.957	2.220	88.15	0.1145	0.02684	0.02221	17.23	0.1891
8		3.653	22.71	21.88	13.61	5.988	5.000	0.1362	2.294	2.430	94.40	0.09531	0.02609	0.02078	20.34	0.2274
9		3.195	19.87	21.95	13.61	6.870	0.6034	0.0164	2.632	2.649	99.38	0.09789	0.03064	0.02425	20.85	0.2339
10		3.953	24.58	21.88	13.61	5.535	-2.931	0.07983	2.120	2.041	103.9	0.1306	0.03303	0.02462	25.46	0.2938

TABLE 18. PERFORMANCE OF SPRAY-ORIFICE SCRUBBER ON AEROSOL D

Test code	Contactor orifice size (cm)	Gas flow rate (std m^3/min)	Gas velocity in orifice (m/sec)	Water rate (liter/min)	Water pressure (atm)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 cm^3)			% P_L	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								Gas P_G	Liquid P_L	Total P_T			In	Out		
SO-D																
1	3.81	4.074	59.55	20.63	13.61	5.064	46.63	1.270	1.940	3.210	60.43	4.498	1.104	0.06054	94.52	2.903
2		3.681	53.81	20.63	13.61	5.604	34.39	0.9369	2.147	3.084	69.62	4.496	1.221	0.09157	92.50	2.591
3		3.214	46.99	20.63	13.61	6.417	21.81	0.5941	2.459	3.053	80.54	3.890	1.210	0.1581	86.93	2.035
4		2.778	40.60	20.63	13.61	7.427	11.06	0.3557	2.845	3.201	88.89	3.103	1.117	0.1831	83.61	1.808
5		2.234	32.66	20.63	13.61	9.234	3.879	0.1057	3.538	3.643	97.10	3.894	1.743	0.2443	85.98	1.965
6		1.592	23.27	20.63	13.61	12.96	-4.698	-0.1280	4.965	4.837	102.6	3.836	2.410	0.1693	92.98	2.656
7		4.064	59.41	18.32	10.21	4.508	49.31	1.343	1.295	2.638	49.09	4.037	0.9935	0.06837	93.12	2.676
8		3.529	51.59	18.24	10.21	5.170	33.53	0.9134	1.486	2.399	61.92	3.105	0.8801	0.1497	82.99	1.771
9		2.907	42.50	18.24	10.21	6.275	19.22	0.5236	1.803	2.327	77.49	3.894	1.339	0.2443	81.76	1.702
10		2.326	34.01	18.19	10.21	7.818	5.344	0.1456	2.246	2.392	93.91	3.347	1.439	0.3238	77.49	1.491
11		0.6178	9.032	18.24	10.21	29.53	-9.913	-0.2700	8.484	8.214	103.3	3.747	6.065	0.1804	97.03	3.515
12		1.397	20.42	18.24	10.21	13.06	-3.491	-0.0951	3.753	3.658	102.6	3.785	2.710	0.3238	88.05	2.125
13		4.024	58.82	15.22	6.804	3.781	52.06	1.418	0.7243	2.143	33.81	3.812	0.9475	0.06235	93.42	2.721
14		3.540	51.75	15.22	6.804	4.298	37.50	1.021	0.8233	1.845	44.63	3.828	1.081	0.1250	88.44	2.158
15		2.907	42.50	15.22	6.804	5.234	22.71	0.6187	1.003	1.621	61.84	3.738	1.286	0.2590	79.85	1.602
16		2.001	29.25	15.22	6.804	7.604	6.939	0.1890	1.457	1.646	88.51	3.483	1.741	0.5642	67.59	1.127
17		1.133	16.57	15.14	6.804	13.36	-2.370	-0.0646	2.559	2.494	102.6	3.356	2.961	0.6289	78.76	1.549
18		0.5273	7.708	15.14	6.804	28.71	-6.379	-0.1738	5.500	5.327	103.3	3.719	7.054	0.4994	92.92	2.648
19		3.953	57.78	11.32	3.402	2.863	55.17	1.503	0.2742	1.777	15.43	3.660	0.9261	0.06386	93.10	2.674
20		3.423	50.04	11.32	3.402	3.306	38.36	1.045	0.3166	1.362	23.26	3.489	1.019	0.1331	86.94	2.035
21		2.893	42.29	11.32	3.402	3.912	25.77	0.7021	0.3746	1.077	34.79	4.059	1.403	0.2961	78.90	1.556
22		1.883	27.53	11.32	3.402	6.009	8.534	0.2325	0.5756	0.8080	71.23	4.234	2.248	0.9988	55.57	0.8113
23		0.1800	2.632	11.32	3.402	62.87	-3.362	-0.0916	6.021	5.929	101.5	2.129	11.82	2.043	82.72	1.756
24		0.7808	11.41	11.32	3.402	14.49	-1.198	-0.0326	1.388	1.356	102.4	4.207	5.388	2.020	62.52	0.9813
25	2.54	2.413	79.38	20.70	13.61	8.579	148.7	4.052	3.287	7.338	44.79	4.342	1.799	0.00994	99.45	5.198
26		2.386	78.48	18.13	10.21	7.599	158.5	4.317	2.183	6.501	33.59	4.346	1.822	0.01266	99.30	4.967
27		2.375	78.13	15.06	6.804	6.342	157.9	4.302	1.215	5.517	22.02	4.152	1.748	0.01117	99.36	5.053
28		2.362	77.68	11.32	3.402	4.792	157.5	4.291	0.459	4.750	9.66	3.913	1.657	0.01268	99.23	4.873
29		2.180	71.69	20.70	13.61	9.499	121.9	3.321	3.639	6.960	52.29	4.096	1.879	0.01542	99.18	4.803
30		2.180	71.69	18.13	10.21	8.318	121.9	3.321	2.390	5.711	41.85	4.036	1.852	0.01753	99.05	4.660
31		2.132	70.11	15.37	6.804	7.209	121.9	3.321	1.381	4.702	29.37	3.893	1.827	0.01934	98.94	4.548
32		2.122	69.79	11.32	3.402	5.334	121.9	3.321	0.5108	3.832	13.33	3.966	1.869	0.02084	98.88	4.496
33		1.894	62.31	20.70	13.61	10.93	78.57	2.140	4.187	6.327	66.18	4.341	2.292	0.03012	98.69	4.332
34		2.032	66.84	18.13	10.21	8.922	78.57	2.140	2.564	4.704	54.50	5.008	2.465	0.04217	98.29	4.068
35		1.792	58.96	15.22	6.804	8.489	78.57	2.140	1.626	3.766	43.17	4.391	2.450	0.05241	97.86	3.845
36		1.745	57.40	11.32	3.402	6.485	78.57	2.140	0.6211	2.761	22.49	4.240	2.430	0.06295	97.41	3.653

TABLE 19. PERFORMANCE OF SPRAY-ORIFICE SCRUBBER ON AEROSOL G

Test code	Contactor orifice size (cm)	Gas flow rate (std m^3/min)	Gas velocity in orifice (m/sec)	Water rate (liter/min)	Water pressure (atm)	Liquid-to-gas ratio (liter/std m^3)	Effective friction loss (cm WC)	Contacting power (kWh/1000 m^3)			% P_L	Aerosol generation rate (mg/min)	Aerosol concentration (mg/std m^3)		Collection efficiency (%)	Transfer units (N_t)
								Gas P_G	Liquid P_L	Total P_T			In	Out		
SO-G																
1	3.81	3.963	57.93	20.70	13.61	5.225	46.55	1.268	2.002	3.270	61.22	0.1303	0.03287	0.01755	46.63	0.6279
2		3.540	51.75	20.70	13.61	5.848	29.91	0.8148	2.240	3.055	73.33	0.1295	0.03658	0.02425	33.72	0.4112
3		2.914	42.60	20.70	13.61	7.104	15.69	0.4274	2.722	3.149	86.43	0.1230	0.04220	0.03261	22.73	0.2579
4		2.254	32.95	20.59	13.61	9.134	3.362	0.0916	3.499	3.591	97.45	0.1173	0.05204	0.03953	24.03	0.2749
5*		0.7393	10.81	20.70	13.61	28.00	-14.05	-0.3827	10.73	10.35	103.7	0.1070	0.1447	0.07861	45.68	0.6103
6*		1.634	23.88	20.70	13.61	12.67	-4.741	-0.1291	4.856	4.726	102.7	0.1063	0.06504	0.04587	29.48	0.3492
7		4.044	59.12	18.32	10.21	4.530	49.13	1.338	1.302	2.640	49.30	0.1077	0.02664	0.01709	35.84	0.4438
8		3.540	51.75	18.24	10.21	5.153	33.92	0.9240	1.481	2.405	61.58	0.1078	0.03046	0.02364	22.37	0.2532
9		2.907	42.50	18.24	10.21	6.275	18.96	0.5166	1.803	2.320	77.73	0.09696	0.03335	0.02703	18.94	0.2100
10		2.132	31.16	18.24	10.21	8.559	5.344	0.1456	2.459	2.605	94.41	0.1115	0.05232	0.04443	15.08	0.1635
11*		0.9816	14.35	18.24	10.21	18.59	-7.413	-0.2019	5.340	5.138	103.9	0.09507	0.09686	0.07628	21.25	0.2388
12*		1.403	20.51	18.24	10.21	13.00	-3.551	-0.0967	3.736	3.640	102.7	0.08148	0.05808	0.05203	10.41	0.1100
13		3.993	58.38	15.22	6.804	3.810	51.46	1.402	0.7299	2.132	34.24	0.1153	0.02888	0.01732	40.03	0.5113
14		3.540	51.75	15.22	6.804	4.298	37.67	1.026	0.8233	1.849	44.52	0.09642	0.02723	0.02011	26.18	0.3035
15		2.907	42.50	15.22	6.804	5.234	22.24	0.6058	1.003	1.608	62.33	0.09722	0.03344	0.02703	19.16	0.2127
16		2.082	30.44	15.22	6.804	7.307	7.887	0.2149	1.400	1.614	86.69	0.08756	0.04205	0.03675	12.61	0.1348
17*		1.328	19.42	15.22	6.804	11.46	-0.8620	-0.0235	2.194	2.171	101.1	0.07431	0.05595	0.05407	3.36	0.0342
18		1.145	16.73	15.22	6.804	13.29	-2.414	-0.0656	2.546	2.480	102.7	0.08302	0.07252	0.05761	20.57	0.2303
19		3.932	57.48	11.39	3.402	2.898	55.17	1.503	0.2775	1.780	15.59	0.1014	0.02579	0.01596	38.11	0.4798
20*		3.552	51.92	11.39	3.402	3.208	41.72	1.136	0.3072	1.444	21.28	0.0836	0.02354	0.01687	28.34	0.3332
21		2.900	42.40	11.39	3.402	3.928	25.75	0.7014	0.3762	1.078	34.91	0.09314	0.03211	0.02771	13.71	0.1475
22		1.872	27.37	11.39	3.402	6.085	8.448	0.2301	0.5828	0.8129	71.69	0.09502	0.05076	0.04789	5.64	0.0581
23		0.809	11.83	11.39	3.402	14.08	-1.215	-0.0331	1.349	1.316	102.5	0.1053	0.1302	0.1087	16.54	0.1808
24*	2.54	2.405	79.10	20.70	13.61	8.609	161.9	4.409	3.298	7.708	42.79	0.1260	0.05239	0.00694	86.76	2.022
25*		2.379	78.25	18.13	10.21	7.621	158.5	4.317	2.190	6.507	33.65	0.1237	0.05199	0.00881	83.05	1.775
26*		2.356	77.50	15.22	6.804	6.457	158.5	4.317	1.237	5.554	22.27	0.1157	0.04910	0.00956	80.52	1.636
27*		2.370	77.96	11.32	3.402	4.775	158.1	4.306	0.4573	4.763	9.60	0.1119	0.04719	0.00956	79.74	1.596
28*		2.122	69.79	20.59	13.61	9.704	121.9	3.321	3.718	7.039	52.82	0.1376	0.06484	0.01363	78.98	1.560
29*		2.157	70.94	18.13	10.21	8.406	121.9	3.321	2.415	5.736	42.11	0.1095	0.05076	0.00836	83.53	1.804
30*		2.141	70.43	15.22	6.804	7.106	121.9	3.321	1.361	4.682	29.07	0.1170	0.05463	0.01062	80.57	1.638
31*		2.122	69.79	11.47	3.402	5.405	121.9	3.321	0.5177	3.839	13.49	0.1072	0.05052	0.01273	74.81	1.379
32		1.850	60.84	20.70	13.61	11.19	81.28	2.214	4.288	6.502	65.95	0.1245	0.06729	0.02771	58.82	0.8872
33		1.857	61.06	18.13	10.21	9.766	81.28	2.214	2.806	5.020	55.90	0.1253	0.06748	0.02914	56.82	0.8397
34*		1.799	59.19	15.22	6.804	8.456	81.28	2.214	1.620	3.834	42.25	0.1067	0.05931	0.01634	72.45	1.289
35*		1.781	58.57	11.32	3.402	6.355	81.28	2.214	0.6087	2.823	21.56	0.1230	0.06909	0.01837	73.41	1.325

*Aerosol unsatisfactory.

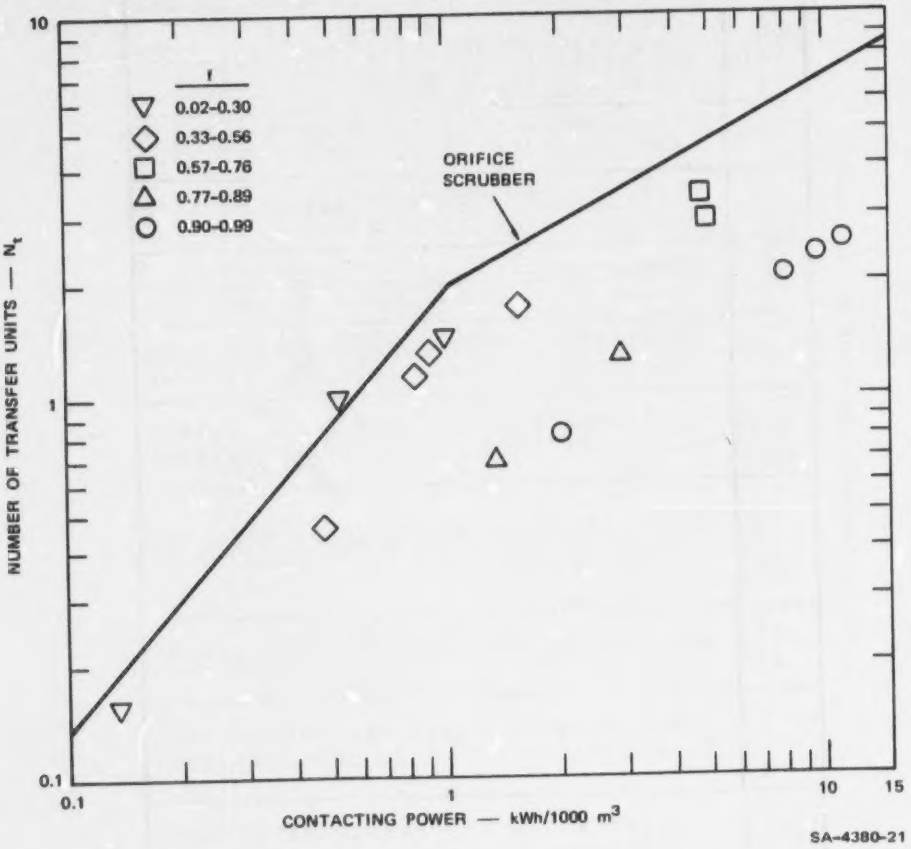

FIGURE 28 CONFIGURATION SS1 SPRAY SCRUBBER PERFORMANCE ON AEROSOL D

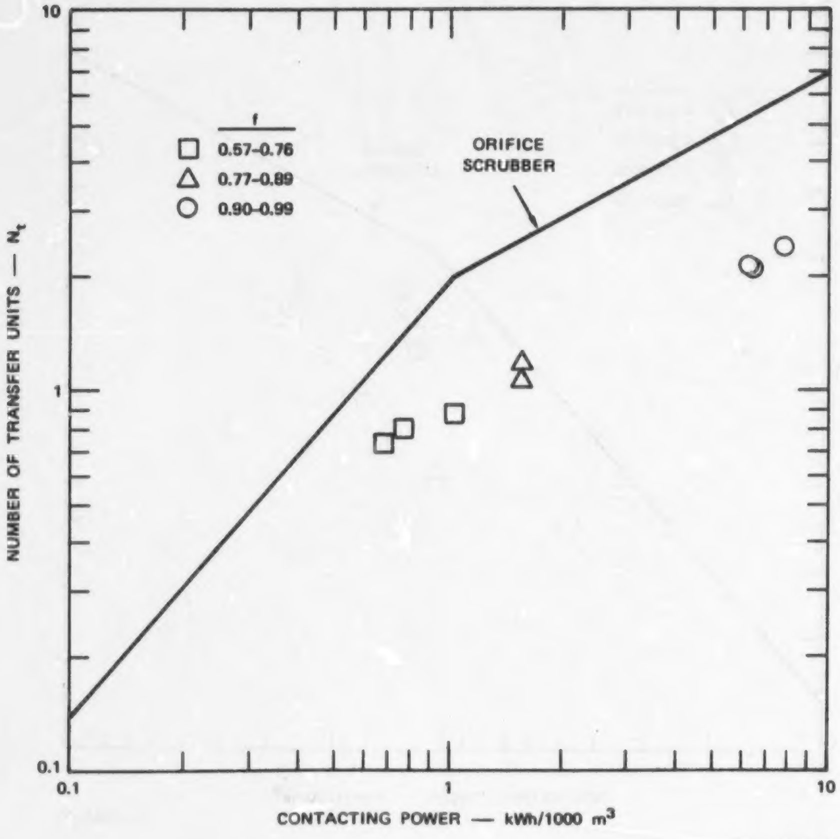

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FIGURE 29 CONFIGURATION SS2 SPRAY SCRUBBER PERFORMANCE ON AEROSOL D

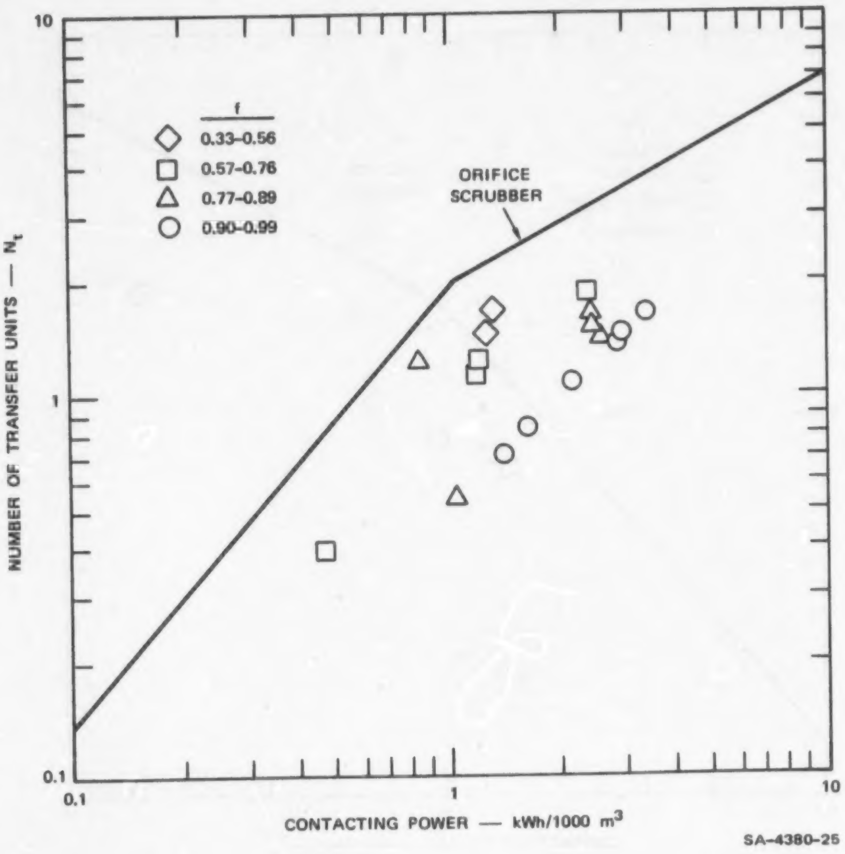

FIGURE 30 CONFIGURATION SS3 SPRAY SCRUBBER PERFORMANCE ON AEROSOL D

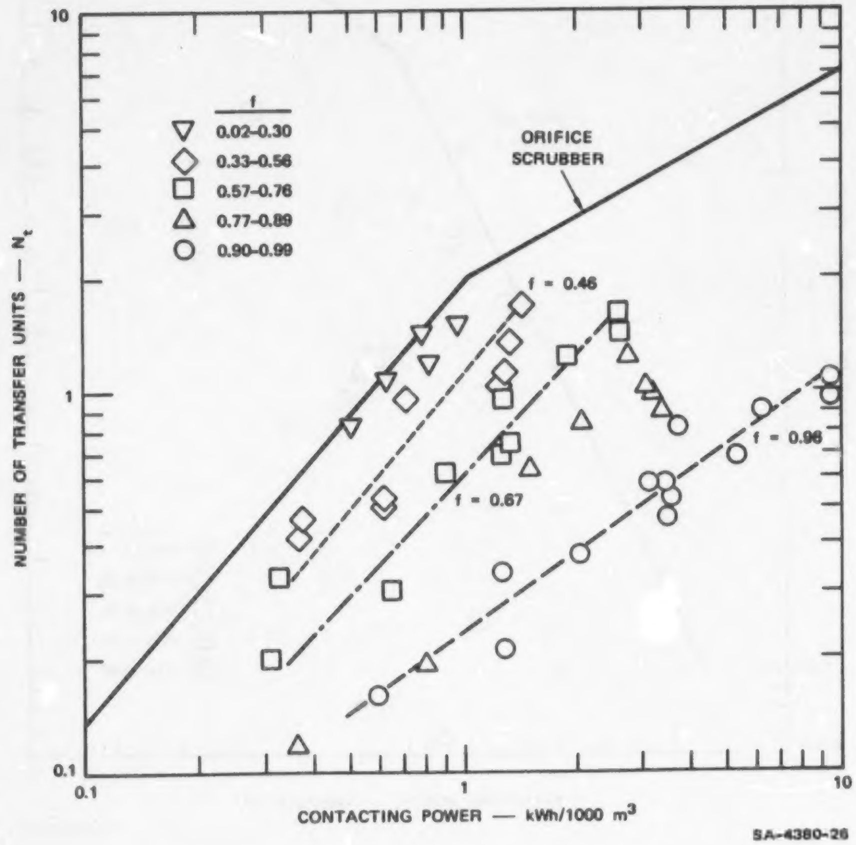

FIGURE 31 CONFIGURATION SS4 SPRAY SCRUBBER PERFORMANCE ON AEROSOL D

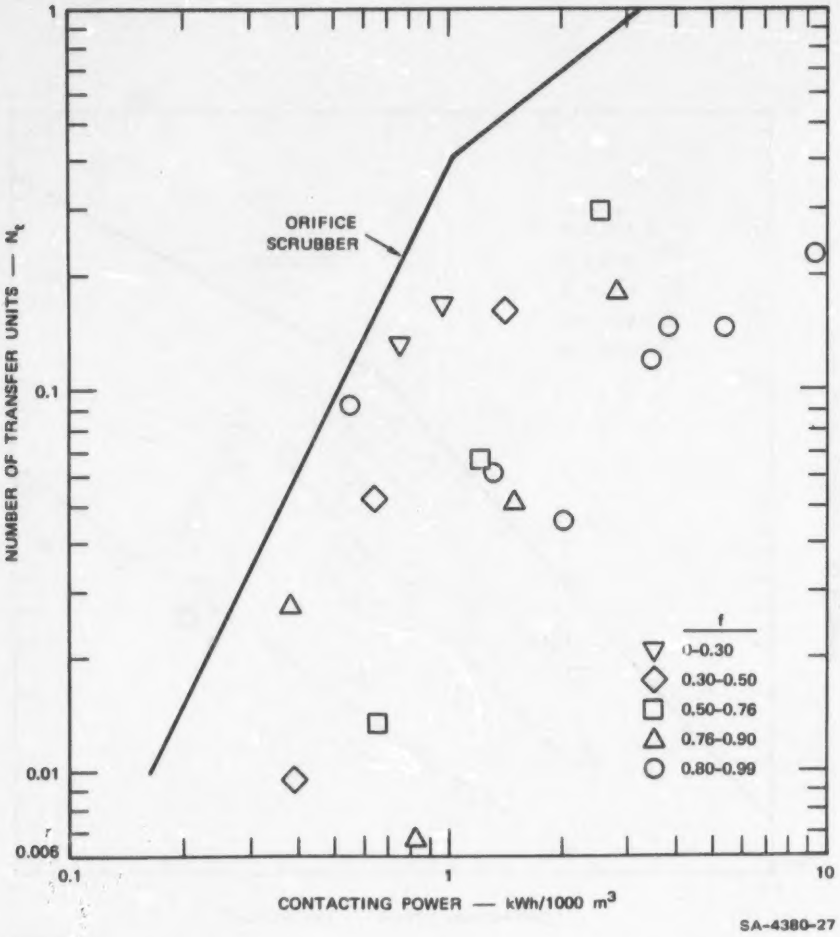

FIGURE 32 CONFIGURATION SS4 SPRAY SCRUBBER PERFORMANCE ON AEROSOL G

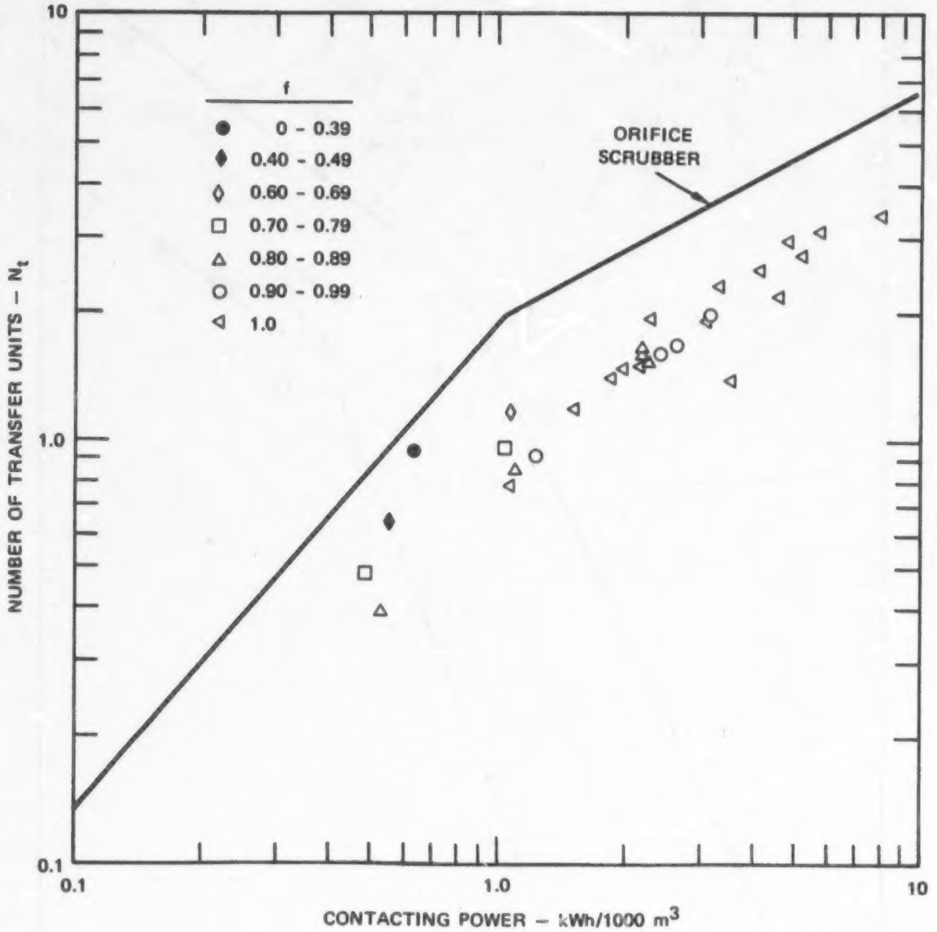

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FIGURE 33 CONFIGURATION SS5 SPRAY SCRUBBER PERFORMANCE ON AEROSOL D

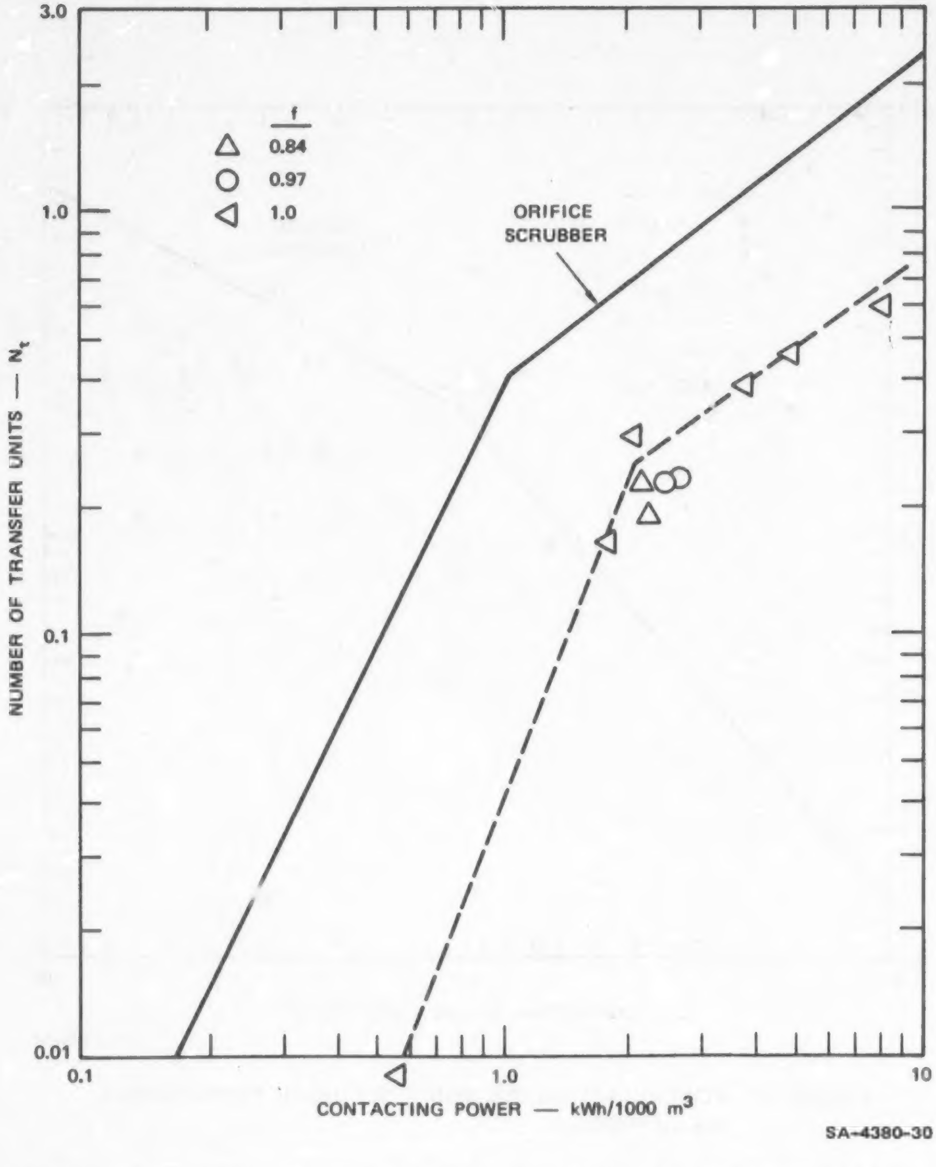

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FIGURE 34 CONFIGURATION SS5 SPRAY SCRUBBER PERFORMANCE ON AEROSOL G

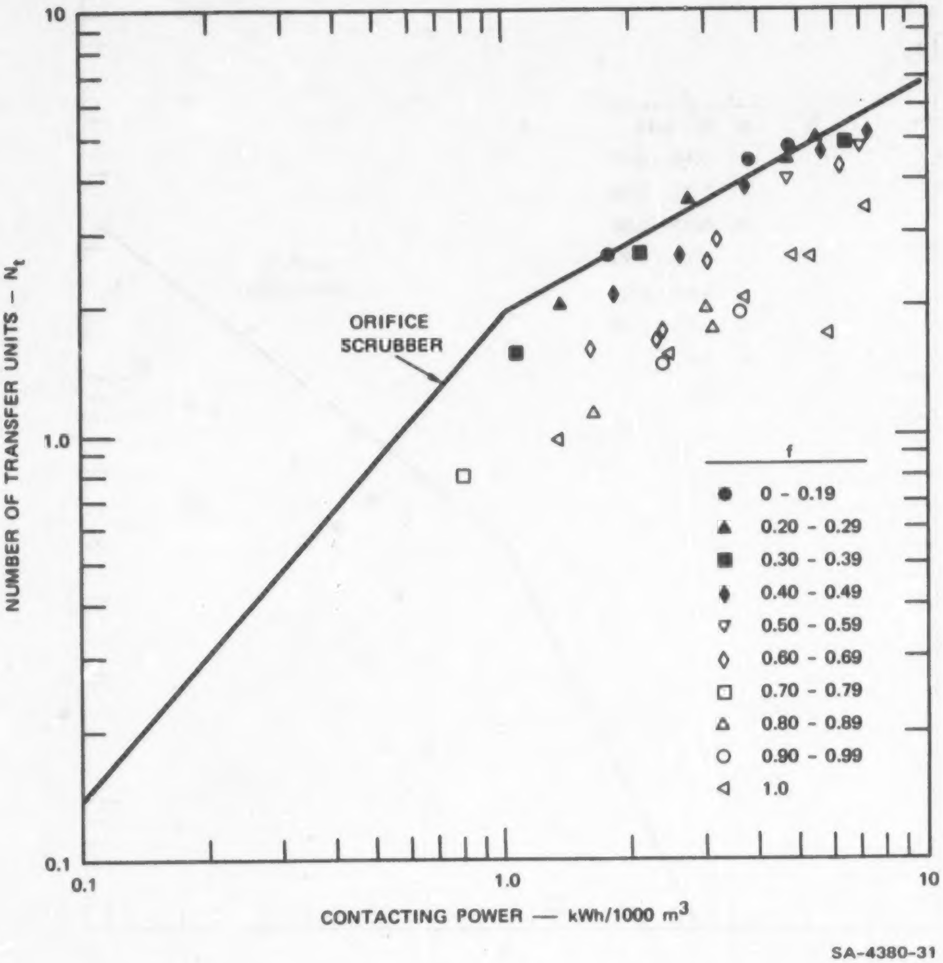

FIGURE 35 SPRAY-ORIFICE SCRUBBER PERFORMANCE ON AEROSOL D

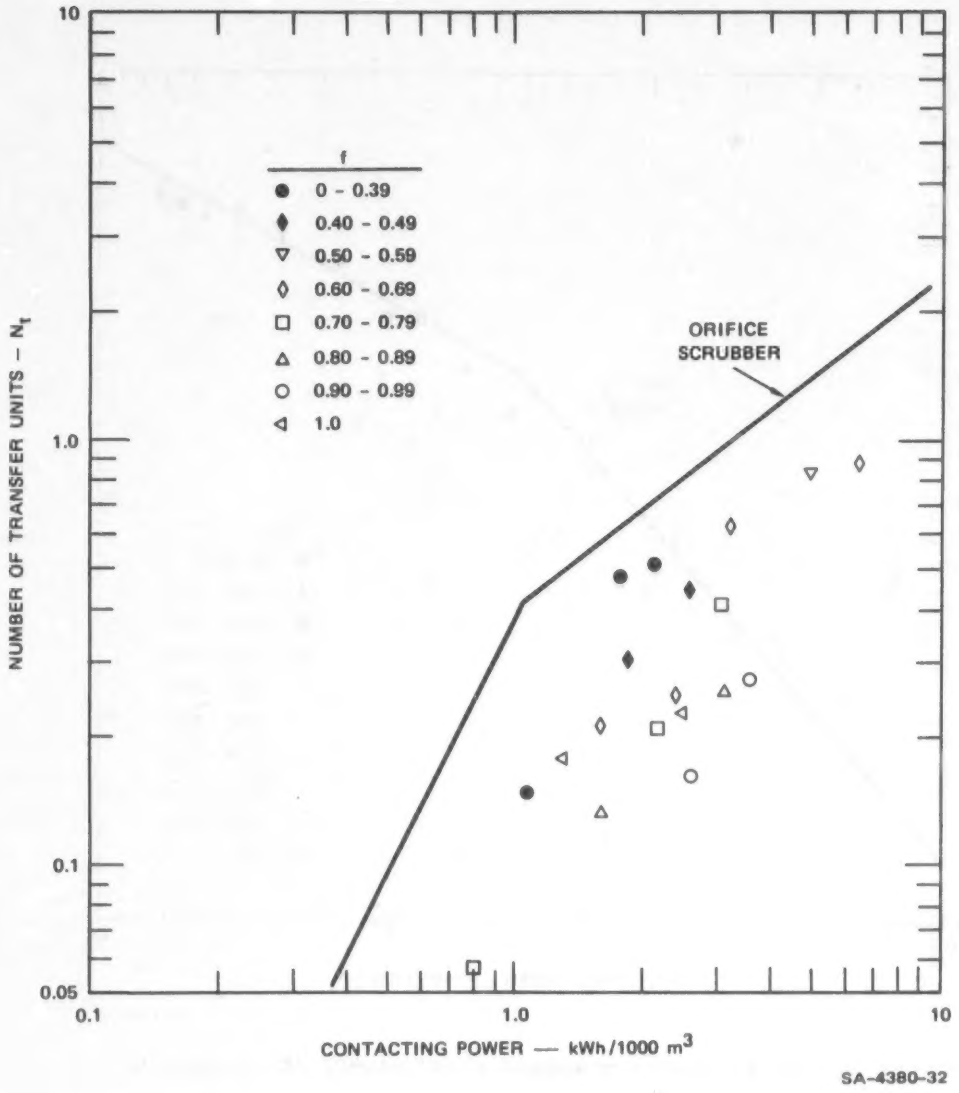

FIGURE 36 SPRAY-ORIFICE SCRUBBER PERFORMANCE ON AEROSOL G

transfer units was plotted as a function of the total contacting power, expressed in units of kWh/1000 m^3. The baseline performance curves for the orifice scrubber are shown in all the figures for reference. The calculations of contacting power and conversion of units were made with the following formulas:

Gas-Phase Contacting Power:

$$P_G = 0.02724\ F_E \qquad \text{kWh/1000 m}^3 \tag{1}$$

where F_E = effective friction loss, cm WC.

Liquid-Phase Contacting Power:

$$P_L = 0.02815\ p_f\ (L/G) \qquad \text{kWh/1000 m}^3 \tag{2}$$

where

p_f = liquid feed pressure, atm gauge
G = gas flow rate, m^3/min
L = liquid flow rate, liters/min.

Total Contacting Power:

$$P_T = P_G + P_L \qquad \text{kWh/1000 m}^3 \quad . \tag{3}$$

Equation (1) is precise, because F_E is a measured value of the gas-phase energy actually consumed in contacting. However, Equation (2) is an approximation, since it gives the theoretical kinetic energy of the water spray emerging from the nozzle. It does not take into account any energy losses that may occur in the nozzle itself, nor any energy losses that may be undergone by the emergent spray in ways that do not contribute to gas/liquid contacting. Direct measurement of the loss in the nozzle would be extremely difficult if practical at all; apparently few if any such data have ever been obtained for spray nozzles. No direct measurement of the energy losses of the spray that are not incidental to gas/liquid contacting appears to be feasible at all. Consequently, the influence of any such losses must be inferred from the performance of the scrubber. Since some energy losses of these natures must take place, it is reasonable to expect that liquid-phase contacting power will in some degree appear inferior to gas-phase contacting power even if the two forms are actually fully equivalent.

Tests of the Configuration SS4 and SS5 spray scrubbers and of the spray-orifice scrubber were made with both Aerosols D and G; the remainder of the spray scrubbers were tested only with Aerosol D.

There was always some gas friction loss attending the flow of the air through the spray scrubbers. Hence, it was not possible to isolate the effects on collection efficiency of liquid-phase contacting power without the interaction of gas-phase contacting power. Tests were made over a wide range of conditions that gave widely varying ratios of liquid-phase to gas-phase contacting power. It was immediately evident that the liquid-phase contacting power and the gas-phase contacting power did not have equal effects on collection efficiency. However, it was not immediately evident how complex the factors in the performance deviation might be.

In a preliminary trial, the efficiency data were assembled in groups according to values of a parameter $\underline{f}$, which is defined as the ratio of the liquid-phase contacting power to the total contacting power. Since there were few runs in which the values of $\underline{f}$ were precisely equal, it was necessary to assemble groups of tests having reasonably narrow ranges of $\underline{f}$ rather than discrete values of the parameter. Nevertheless, inspection of the graphs (Figures 28-31) indicated that the deviations of the spray scrubber data from the baseline orifice scrubber curve could probably be correlated as functions of $\underline{f}$ alone. In Figure 31, the type of relationship is illustrated approximately by the three parametric curves corresponding to groups of points having different average $\underline{f}$ values. Furthermore, scrubber Configurations SS1, SS2, and SS3 appeared to give essentially the same performance, but Configuration SS4 gave much poorer performance than the first three. The same type of behavior appeared in tests of Configuration SS4 with Aerosol G (Figure 32).

In the Configuration SS5 spray scrubber, the water jet produced enough draft to maintain a flow of air through the scrubber without use of the blower. Operated in this manner, the SS5 scrubber represented the class of ejector-venturi scrubbers, which are popular for a variety of gas-cleaning operations. Because the cocurrent, concentric nozzle was located in a straight run of pipe, the water jet was less efficient in producing draft than it would have been had it been located at the inlet of a venturi. However, in other respects the performance of SS5 should have been comparable to that of commercial ejector-venturi scrubbers. For a given water pressure and flow rate, the air flow through the scrubber was determined by the resistance, and was controlled by varying the resistance to air discharge downstream of the scrubber. When the scrubber was operated in this "ejector mode," there was always a net rise in pressure across the scrubber.

The SS5 scrubber could also be operated with the blower on, increasing the air flow to a level at which there was a net pressure drop across the scrubber. In such a case, the draft was produced by both the blower and the water jet. Where the scrubber was operated in the ejector mode, the total contacting power was calculated by subtracting the power equivalent to the gas pressure rise from the total power supplied by the water jet (see Tables 16 and 17). Typically, the total power supplied in the jet was about 1.05 times the calculated total contacting power. Nominally, the value of f was 1.0 in these cases, since all the contacting power came from the water jet. However, some of this power dissipation actually took place as gas-phase friction loss, which may have had a significant effect on the performance of the scrubber. This point is discussed in more detail below.

The performances of the Configuration SS5 scrubber on Aerosols D and G are shown in Figures 33 and 34. The data points corresponding to f = 1.0 were taken with the scrubber operating in the ejector mode. The performance on Aerosol D was evidently very similar to those of Configurations SS1, SS2, and SS3.

The tests with the spray-orifice contactor were designed to determine whether the contribution of the liquid-stream energy could be improved by close combination of the spray with the action of the gas-phase turbulence promoter, the orifice. The 60° spray nozzle was positioned so that the spray would cover the area of the orifice. The jet also produced enough draft that the scrubber could be operated in the ejector mode, without use of the blower. The test results on Aerosol D are presented in Figure 35 and Table 18, and those on Aerosol G in Figure 36 and Table 19. The value of the tests on Aerosol G was reduced because wide variations in the aerosol (revealed by the signatures) required excluding many of the data points (see Table 19).

With the spray-orifice scrubber, numerous runs were made at low values of f; the data points fell close to the baseline orifice scrubber performance curve (Figure 35). However, for runs at higher values of f, the data generally agreed closely with those for the Configuration SS5. Evidently, no advantage was gained by combining the action of the orifice with that of the spray.

To permit a comparison of the different spray scrubber configurations and the spray-orifice scrubber, the data were rationalized in a series of graphs (Figures 37-45) in which the data for all the scrubbers corresponding to given ranges of f were plotted together. For Aerosol D and f = 0-0.39, the data points for all the configurations fell close to the baseline curve (Figure 37). Some scatter could be expected because of the relatively wide range of f values, although all the values were low. It is notable that the data points fell along both branches of the orifice scrubber performance curve included in the figure for reference. This tends to support a view that the two-branched performance curve is characteristic of the aerosol and not of the orifice scrubber itself.

At values of f in the range 0.40-0.59, the differences in scrubber unit performance started to emerge (Figure 38). The data points for the SS5 spray scrubber and the spray-orifice scrubber continued to lie close to the orifice scrubber curve. Those for SS1 and SS3 deviated substantially, and those for SS4 deviated still more. The two additional performance curves, one for SS1 and SS3 and the other for SS4 (broken lines),

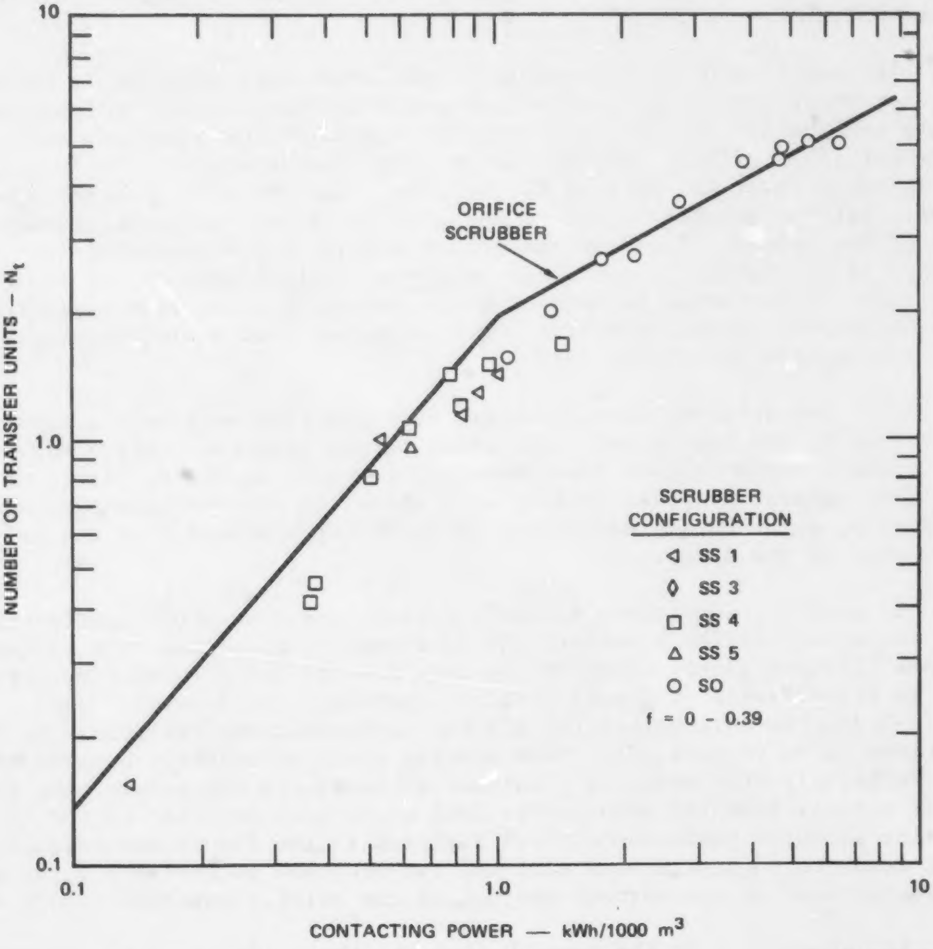

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FIGURE 37 PERFORMANCE OF SPRAY SCRUBBERS ON AEROSOL D AT VALUES OF f = 0 - 0.39

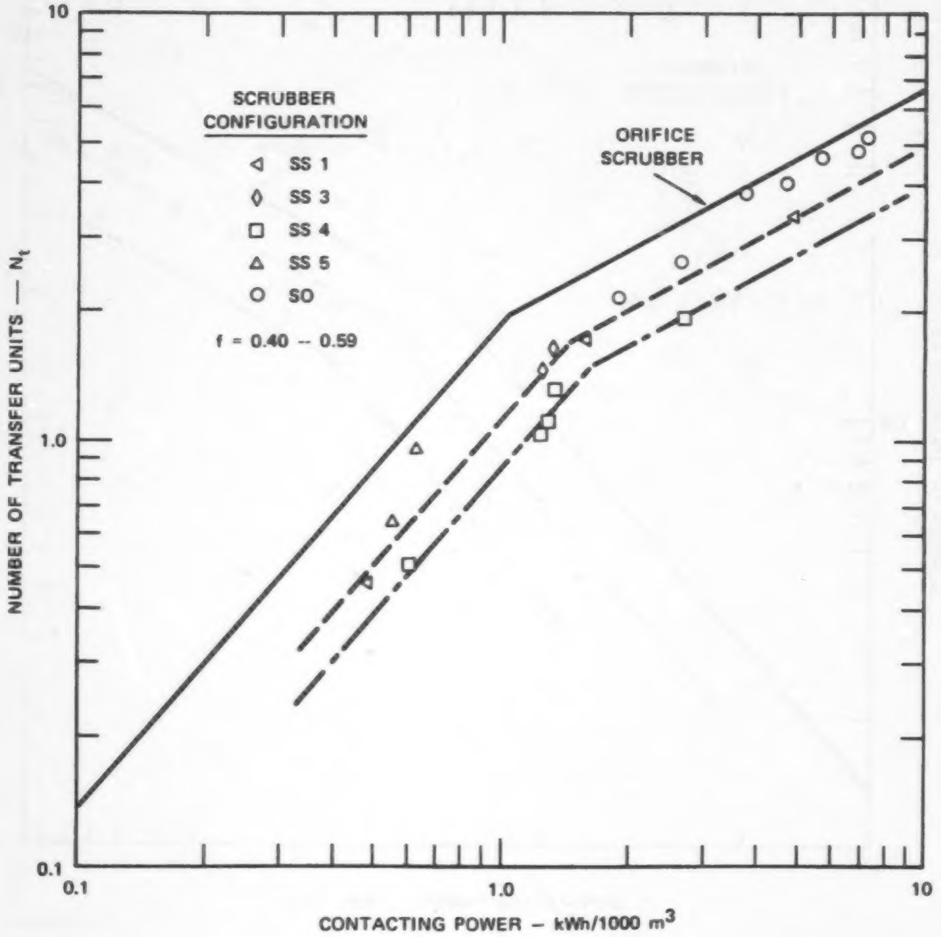

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FIGURE 38 PERFORMANCE OF SPRAY SCRUBBERS ON AEROSOL D AT VALUES OF f = 0.40 - 0.59

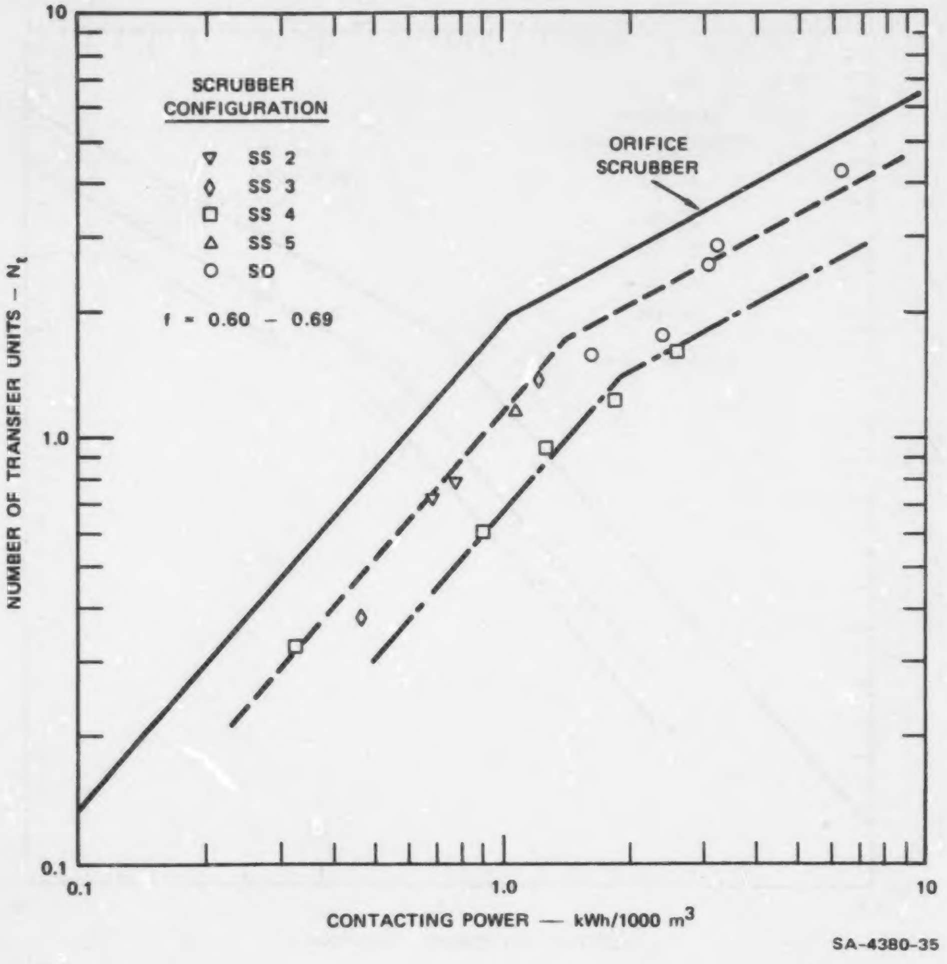

FIGURE 39 PERFORMANCE OF SPRAY SCRUBBERS ON AEROSOL D AT VALUES OF f = 0.60 - 0.69

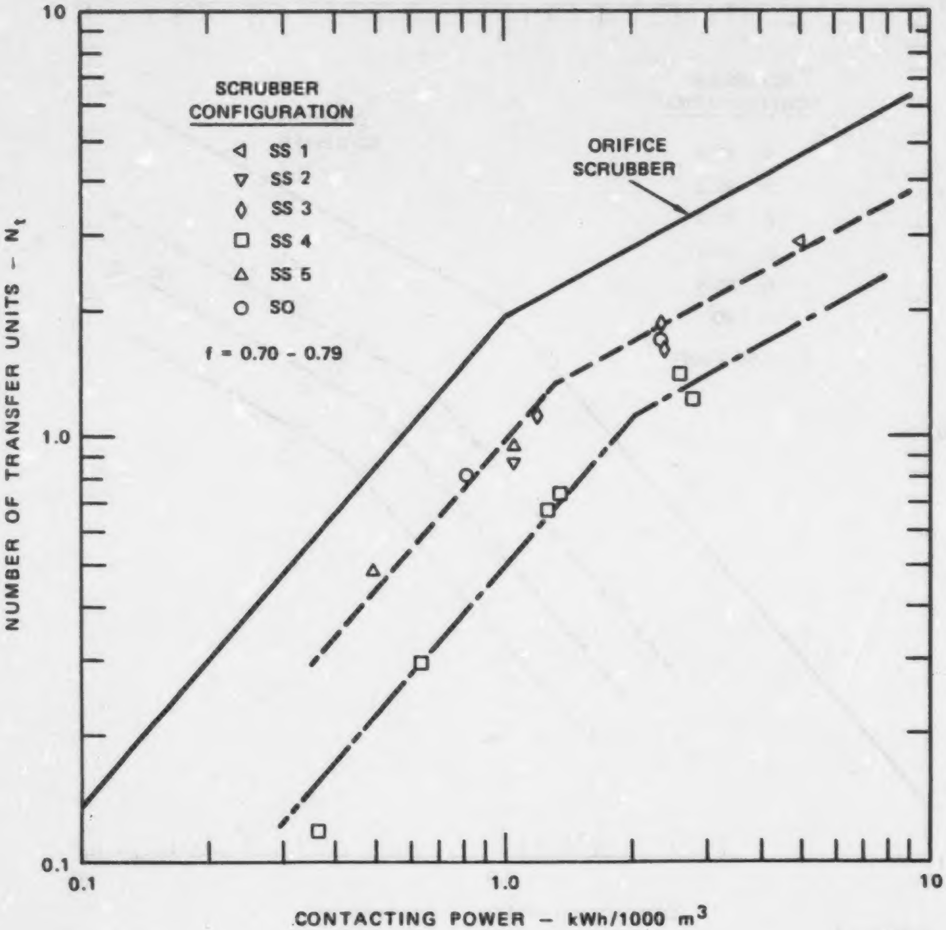

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FIGURE 40 PERFORMANCE OF SPRAY SCRUBBERS ON AEROSOL D AT VALUES OF f = 0.70 - 0.79

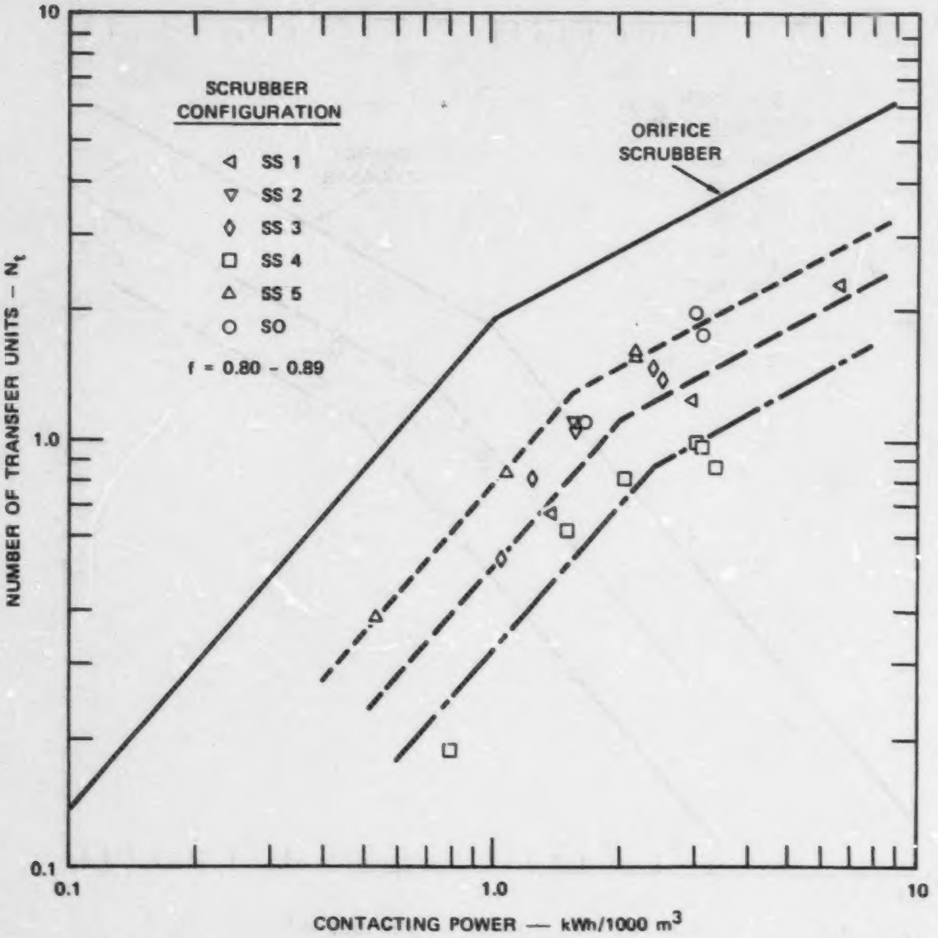

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FIGURE 41 PERFORMANCE OF SPRAY SCRUBBERS ON AEROSOL D AT VALUES OF f = 0.80 - 0.89

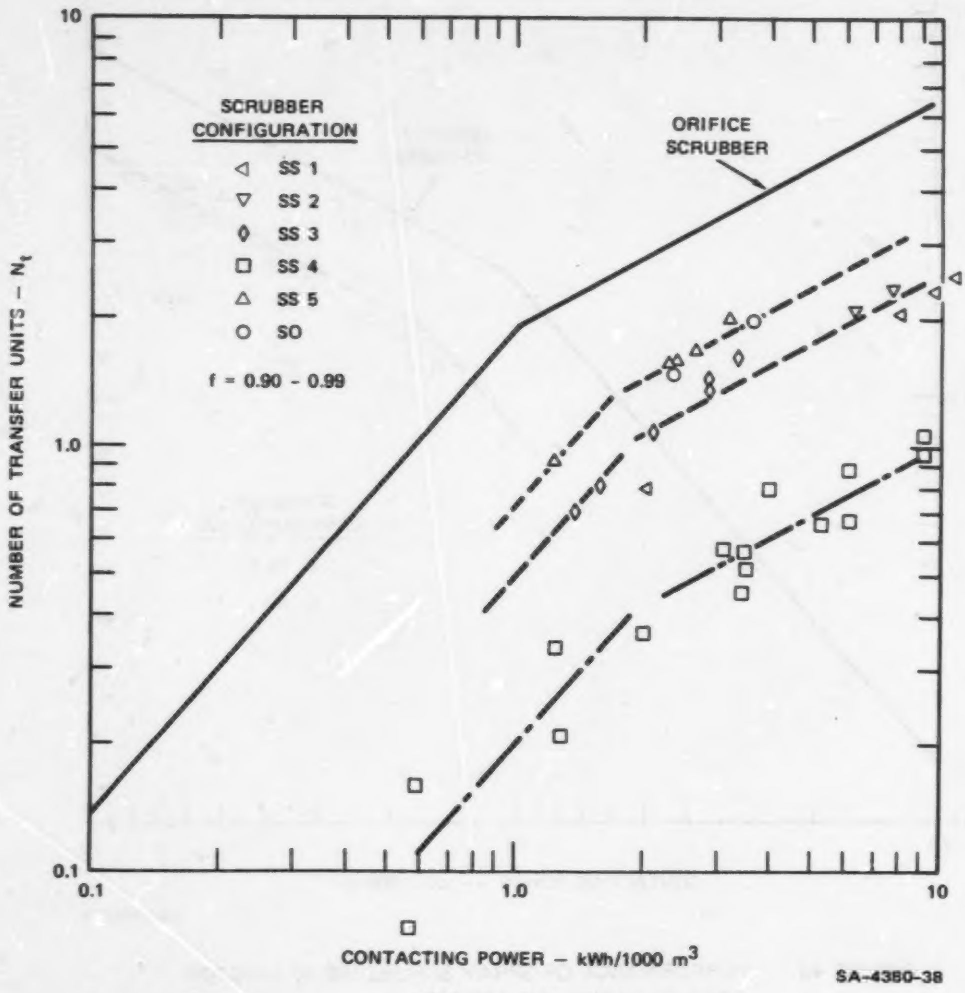

FIGURE 42 PERFORMANCE OF SPRAY SCRUBBERS ON AEROSOL D AT VALUES OF f = 0.90 - 0.99

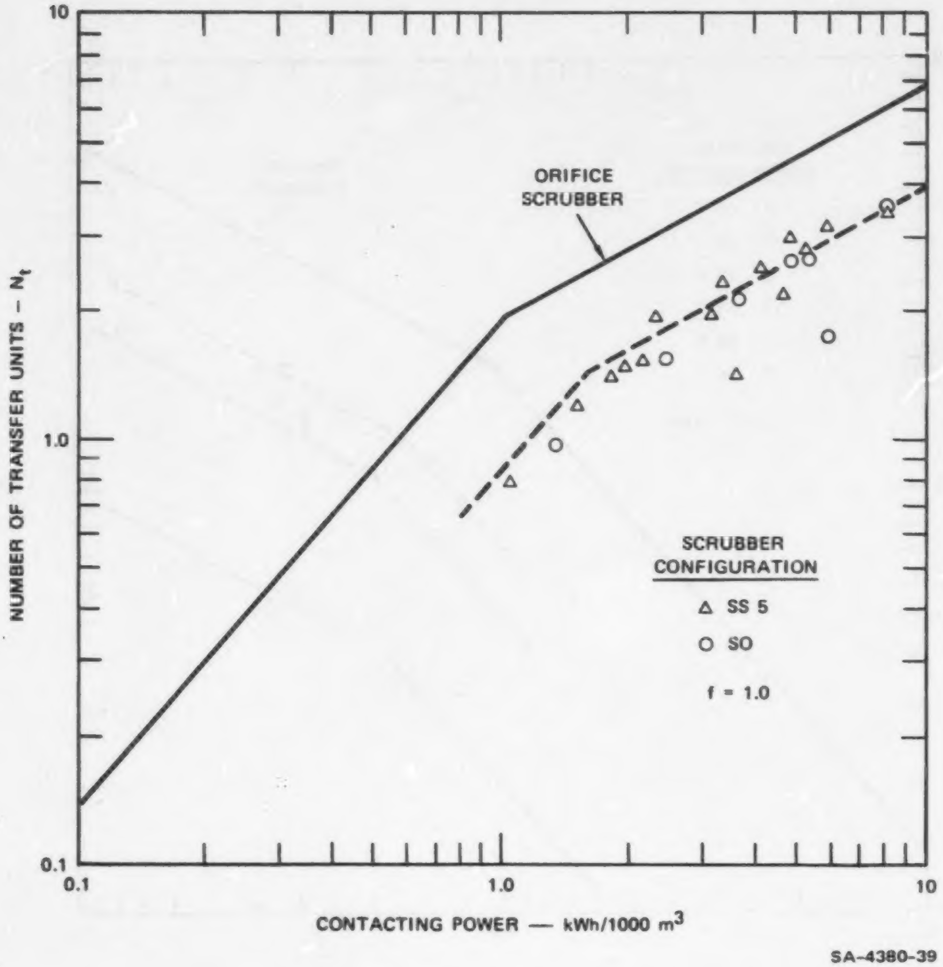

FIGURE 43 PERFORMANCE OF SPRAY SCRUBBERS IN EJECTOR CONFIGURATION ON AEROSOL D

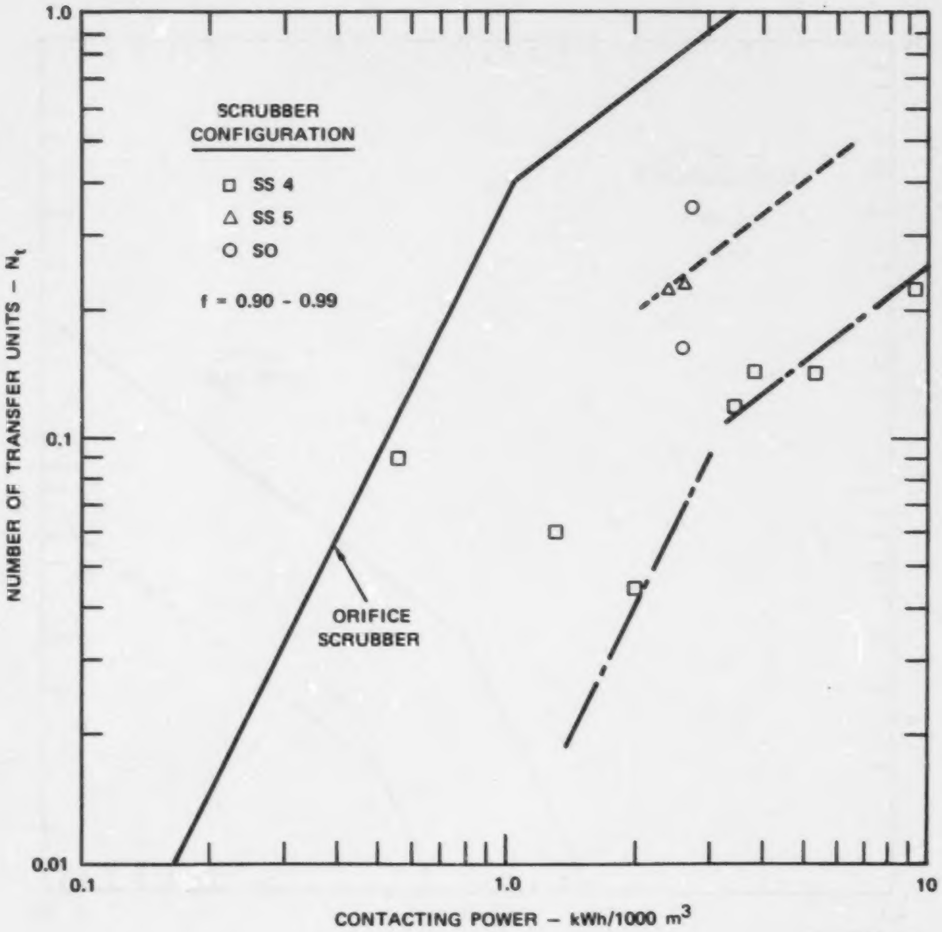

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FIGURE 44 PERFORMANCE OF SPRAY SCRUBBERS ON AEROSOL G AT VALUES OF f = 0.90 - 0.99

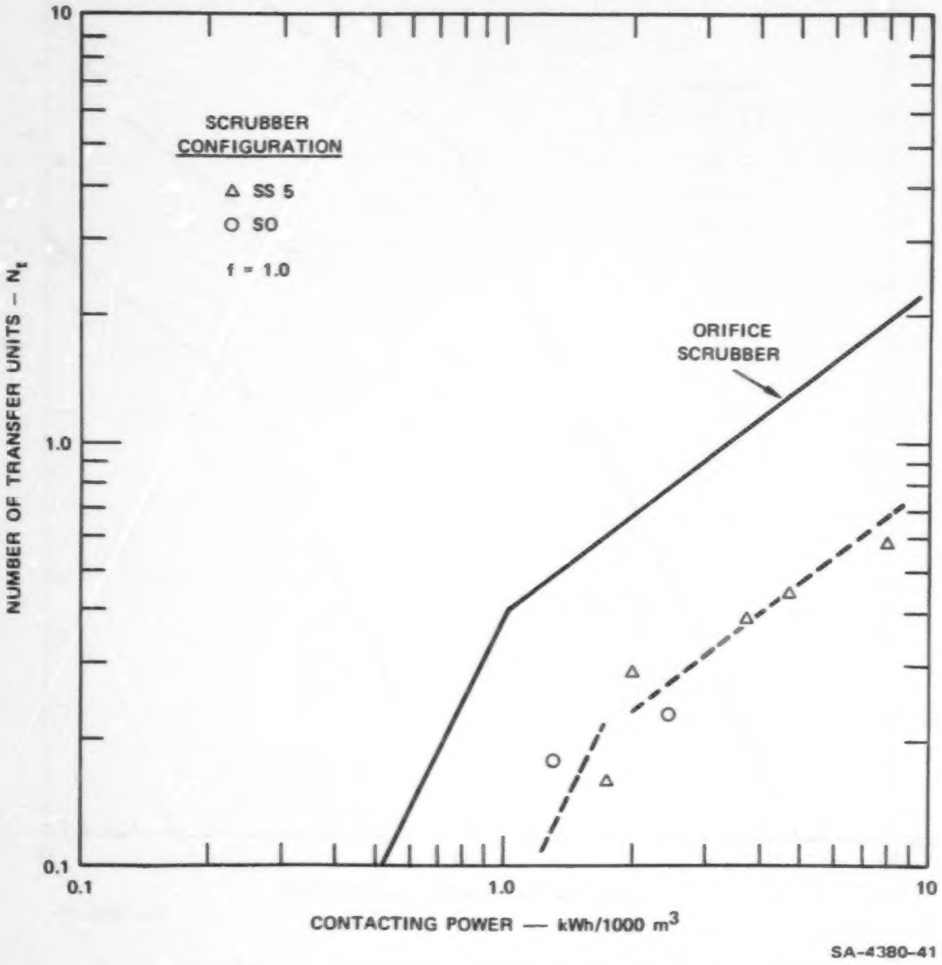

FIGURE 45 PERFORMANCE OF SPRAY SCRUBBERS IN EJECTOR CONFIGURATION ON AEROSOL G

were arbitrarily drawn in parallel to the branches of the orifice scrubber curve; the cumulative evidence of these data and those in the subsequent Figures 39-45 indicates that the assumption of parallel curves is probably reasonable.

At values of _f_ in the range 0.60-0.69, all the data points deviated markedly from the orifice scrubber curve (Figure 39). No distinction could be made among the data for SS2, SS3, SS5, and the spray-orifice scrubber, but SS4 again gave distinctly poorer performance. The same behavior appeared at _f_ values of 0.70-0.79 (Figure 40). However, at _f_ values of 0.80-0.89 a separation appeared between the group of data points for SS1, SS2, and SS3 and the group for SS5 and the spray-orifice scrubber (Figure 41). The same condition appeared, in accentuated degree, at _f_ values in the range 0.90-0.99 (Figure 42).

The performances of the SS5 and spray orifice scrubbers when operated in the ejector mode (_f_ = 1.0) are shown in Figure 43. Within the precision of the data there was no difference in the performances of the two devices. Although the curves drawn in Figures 42 and 43 indicate that the ejector configuration of the SS5 and spray orifice scrubbers gave somewhat higher efficiency than the same devices at _f_ = 0.90-0.99, it is not clear whether the difference is actually significant.

The performances of the spray scrubbers on Aerosol G are similarly presented for _f_ = 0.90-0.99 (Figure 44) and for the ejector configurations (Figure 45). The results are generally qualitatively in accord with those obtained with Aerosol D. However, the relative deviation of spray scrubber data from the baseline orifice scrubber curves was markedly greater for Aerosol G than for Aerosol D, which shows directly that the relative inefficiency of liquid-phase contacting power, compared with gas-phase contacting power, becomes greater as aerosol particle size decreases.

GENERAL DISCUSSION

Comparison with Previous Studies

In both the present investigation and the preceding one,[6] the performance of the orifice scrubber was demonstrated to be dependent (for a given aerosol) only on the effective friction loss, and not to be independently affected by gas velocity, liquid-to-gas ratio, or orifice size. This finding supported earlier experience with other scrubbers and other aerosols[1-5] as well as reports by other investigators (see Appendix A). However, still other investigators have continued to report finding independent effects of gas velocity, liquid rate, method of water injection, and other such variables. In some unpublished studies of venturi scrubber performance, Semrau[2] found instances of relatively inferior performance at low liquid-to-gas ratios in the range of 0.1-0.4 liters/m^3 (1-3 gal/1000 ft^3). The recent tests with the orifice scrubber were always made with substantially higher liquid-to-gas ratios. Other discrepancies in reported scrubber behavior are less readily accounted for, although the methods of testing may have been involved in at least some instances.

In the unpublished studies,[2] a bench-scale contactor that generally simulated the Greenburg-Smith impinger gave the same performance as the venturi and orifice scrubbers at low effective friction losses, but showed increasingly inferior performance as the air jet velocity was increased to increase the effective friction loss. Consideration of all such experience led the present author to conclude that the performance curve determined for a given aerosol with well-designed orifice and venturi scrubbers (and presumably other designs as well) probably represents the maximum scrubber performance attainable, although certain scrubber configurations and/or modes of operation may give poorer performance.

Performance Curves

The present investigation, like the preceding one on "Wet Scrubber Liquid Utilization,"[6] has again affirmed the straight-line form of scrubber performance curves, although revealing the added complexity of two-branched curves. The basis of the straight-line form is empirical. Although Calvert et al.[8] have derived an equation for venturi scrubbers that predicts a straight line having a slope of 1.0 for a monodisperse aerosol, it is not obvious that a straight-line form should necessarily hold for polydisperse aerosols in general.

The two-branched curves afford still less explanation, even if it is assumed that the two branches are not actually composed of precisely straight lines. Two-branched curves first appeared in the preceding study[6] with the same orifice scrubber. The ammonium fluorescein aerosol used in that investigation was found to vary quite widely because of the instability of the generator. In tests with ambient air as the gas, two-branched curves appeared in varying degrees for some of the variant forms of the aerosol, and not at all for one or two forms. No lower branch appeared in tests at adiabatic saturation and condensing conditions, but the appearance of a lower branch was very marked under vaporizing conditions. In the present investigation, two-branched curves appeared in studies of all the test aerosols except possibly Aerosol F. In addition, two-branched curves evidently appeared in tests of the spray scrubbers. It is therefore evident that the two-branched curve is a property of the aerosol, not the scrubber.

There is still no satisfactory general interpretation for the slopes of the scrubber performance curves. Slopes less than 1.0, which have most often been encountered in various investigations, indicate that collection of an aerosol becomes progressively more difficult as higher collection efficiencies are attained at higher levels of contacting power. This is in accord with both theoretical and empirical evidence that coarse particles are more readily collected than finer ones, at least in the range in which inertial collection is dominant. It was hypothesized earlier[5] that a precisely monodisperse aerosol should give a performance curve with a slope of 1.0. There is little chance for an experimental confirmation of this hypothesis, since production of an adequately monodisperse aerosol on a scale adequate for scrubber testing appears to be infeasible. Furthermore, slopes of approximately 1.0 have appeared in curves for aerosols that were not even nominally monodisperse.[5] Finally, performance curves with slopes greater than 1.0 have appeared. These appeared first in correlations of data from the literature,[4,5] but have now appeared in the present investigation and its predecessor.[6] In these last cases the lower branches have always had slopes greater than 1.0. The single performance curve for Aerosol F had a slope greater than 1.0, but greater data precision might have shown a two-branched curve in this case, also.

A performance curve slope greater than 1.0 indicates that the aerosol becomes more readily collectable as higher collection efficiencies are attained with increasing contacting power. It is difficult to visualize any single collection mechanism that would give such behavior. Inertia gives preferential collection of larger particles and diffusion preferential collection of finer particles. Either mechanism operating alone should presumably give a performance curve with a slope less than 1.0, since operation at higher contacting powers and efficiencies would result in preferential depletion of the more readily collectable fraction of the aerosol. Possibly the steep lower branch of the performance curve represents a region in which both diffusion and inertia were operative but neither was strongly dominant. The lower branch did represent a region of relatively low overall efficiency. On aerosols of the sizes under study, the inertial collection efficiency was low in this contacting power range, and presumably collection by diffusion was low in any case. However, if both mechanisms were increasing in effectiveness in this region of operation, it seems that some such behavior as was observed might result. This would certainly depend on how the efficiency of each mechanism was varying with contacting power and how these efficiencies were varying with respect to each other.

The "knee" in the performance curve, or transition from the lower branch to the upper branch, possibly represents the point (or narrow region) at which inertial deposition reached such effectiveness that it clearly dominated the overall collection efficiency.

The foregoing speculations are probably still too crude to be termed a hypothesis. Nevertheless, projecting some such combination of mechanisms seems necessary to permit visualizing a physical process that could yield the observed phenomena.

Particle Size/Efficiency Relationships

The performance of the orifice scrubber is presented in Figure 46 as a function of the aerosol mass-median particle diameter as determined from the cascade impactor tests (Table 3). The number of transfer units

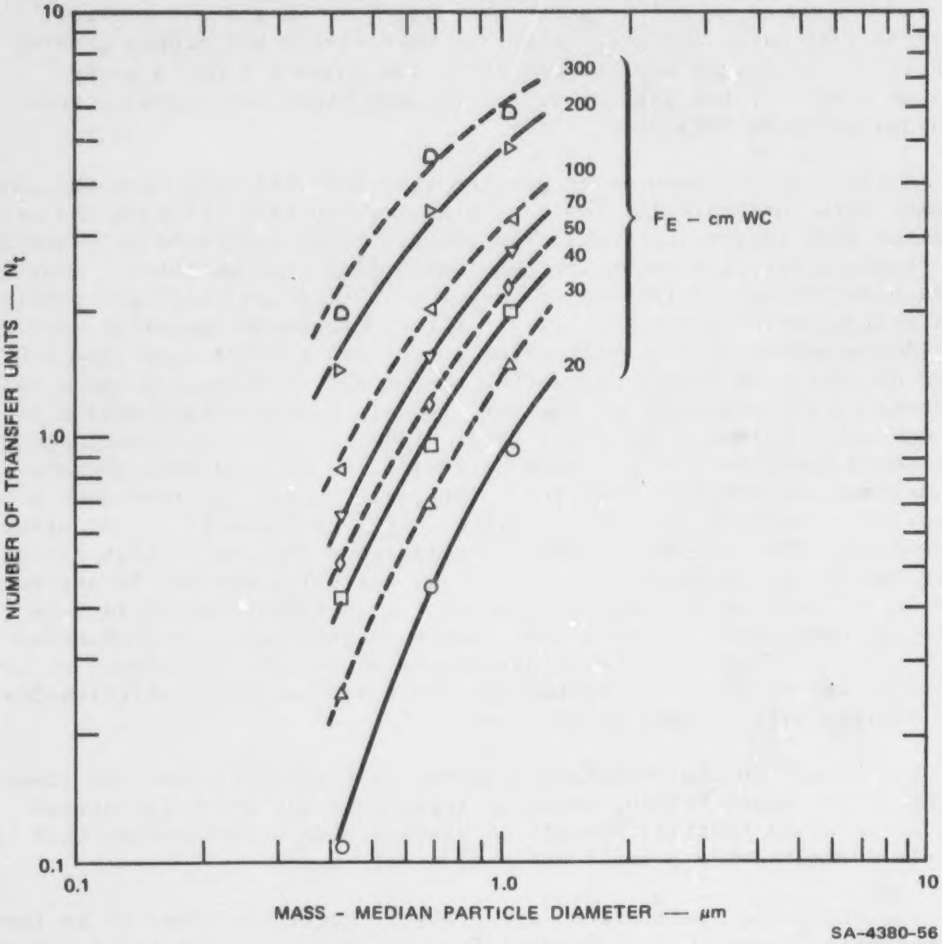

FIGURE 46 PERFORMANCE OF ORIFICE SCRUBBER AS A FUNCTION OF AEROSOL PARTICLE SIZE

is shown with values of the effective friction loss as parameters. The performance data were cross-plotted from Figures 20, 21, and 23.

The curves in Figure 46 can be interpreted only in a relative way. Because the aerosols are polydisperse and have fairly wide particle-size distributions, their collection characteristics are not adequately described in terms of the mean particle size. Particularly in the low-efficiency range, the portion of an aerosol being collected will tend to be comprised mostly of particles larger than the mean size (unless the speculation advanced above is valid).

Series Scrubbing

Although the early study by Lapple and Kamack[1] showed some improvement in performance when an orifice and a venturi contactor were used in series, subsequent experience[2,4,5] did not show any clear differences in scrubber performance when combination contactors were used. Following the study by Semrau and Witham,[6] Cooper[19,20] derived relationships purporting to show that series scrubbing could give higher efficiencies on a specific aerosol than single-stage scrubbing. However, Cooper's derivations require unrealistic premises, and his conclusions would not apply to any real situation (see Appendix A). Conceivably, a series contactor might be found empirically to give performance that is better, the same as, or (as was actually observed in the present study) poorer than that of a single-stage contactor. However, there is nothing in the previous experience[1-7] to suggest that series contacting should give performance systematically different from that of single-stage contactors. In the present study, the performance of the multiple-orifice series contactor probably represents a case in which a specific contactor gives performance inferior to the "maximum performance curve" established with the orifice scrubber. It does not necessarily follow that all series contactors or scrubbers in series should give inferior performance.

Spray Scrubbing

The results of the present investigation have apparently disproved the earlier hypothesis[5] that liquid-phase contacting power is equivalent to gas-phase contacting power, although earlier data appeared to support it. However, it is still not clear whether liquid-phase contacting power is actually inferior to gas-phase contacting power, or whether the apparent difference is due only to the difficulty of evaluating the actual (rather than the nominal) contacting power, as is discussed above. An additional question is raised by the new data that showed that the deviation of spray contactor performance from the performance curve established for gas-phase contacting power decreased with an increase in aerosol particle size. If this trend holds with aerosols larger than those used in this investigation, it may be that for coarser aerosols (perhaps 2-3μm and larger) there is relatively little difference in the effectiveness of gas-phase and liquid-phase contacting power. If so, this would account for some of the earlier results[5] that were obtained with relatively coarse aerosols.

There are, of course, some friction losses in the nozzles, although the losses appear likely to be fairly small except in Configuration SS4. The construction of the SS4 nozzle indicates that the internal friction may consume a substantial part of the input power, which may explain the marked inferiority of the SS4 performance.

The rest of the spray scrubber configurations gave generally similar performance, although Configuration SS5 and the spray-orifice contactor SO definitely gave somewhat better performance than SS1, SS2, and SS3. The similarity of the performances appears quite remarkable considering the extreme divergences in the natures of the sprays and in their orientations with respect to the gas stream. The wide-angle spray nozzle SS3, the 60° spray nozzle used in the spray-orifice scrubber, and the 30° injector nozzle used in SS5 all were equipped with internal spin vanes, so that the stream of water emerging from a nozzle was rotating in a plane normal to the axis. The streams of water thus possessed kinetic energy due both to the velocity of translation and to the rotation of the liquid. The 30° injector nozzle delivered a coarse spray, while the 60° and wide-angle (about 100°) nozzles delivered successively finer sprays. The actual angles of spray discharge were presumably modified by the air flow.

The SS2 nozzle delivered a flat, fan spray normal to the direction of gas flow. Since the spray entered the contacting line from one side, the sheet of water was presumably largely broken up by the crossflow of the air. On the other hand, the concentric perforated tube SS1 delivered high velocity solid jets of water that should have traversed the gas stream and impacted almost normally against the contacting line wall. Atomization probably took place mostly upon impact of the water jets against the wall.

Presumably, any of the kinetic energy of a liquid spray that is not converted ultimately into turbulence and heat in the gas stream will not be effective as contacting power. If spray should collide inelastically with a wall of the scrubber, and the kinetic energy should be converted to heat in the film on the wall, the equivalent energy would be lost for scrubbing purposes. A coarse spray discharged through a gas stream should logically be expected to have retained more of its initial velocity and energy upon reaching a wall than would a fine spray, and thus tend to lose more of its energy at the wall. Unfortunately, there appears to be no way to determine any such losses directly.

It has been suggested that kinetic energy losses on the contacting line walls may account for the apparent inferiority of the liquid-phase contacting power. The overall inferiority of liquid-phase contacting power would be consistent with that explanation (whether correct or not), but the relative performances of the different nozzles are contradictory. The SS5 spray (30°) should travel farther before reaching the wall than would the other solid-cone sprays, but its droplet size was large. The nominal 60° spray angle of the SO contactor should be contracted by the air flow through the orifice, and the spray should have been finer. If anything, the SO spray might be expected to lose less of its energy to the walls than the SS5 spray, but the two devices gave the same performance. It would appear most logical for the SS1 spray to give by far the poorest performance of all the devices if wall losses are the dominant influence, but it gave essentially the same results as did the SS2 and SS3 sprays.

These contradictions do not exclude the possibility that wall losses are a significant factor, but they certainly indicate that the phenomena involved are not simply accounted for. The impact of sprays on the walls is not necessarily inelastic--at least, not completely so. If the impact of the SS1 water jets on the contacting line wall was not elastic, it is difficult to see how the contactor could perform as well as it did.

There is yet another factor involved in the performance of the Configuration SS5 and the spray-orifice contactors. When the Configuration SS5 and spray-orifice contactors were operated in the ejector mode, there was a net rise in gas pressure across the scrubber, but there was also a pressure drop (magnitude not determined) across the scrubber downstream of the section in which the kinetic energy of the water jet was transformed into gas stream pressure. This gas pressure drop, or friction loss, constituted gas-phase contacting power even though the original source of the energy was the liquid stream and the nominal total contacting power was computed as liquid-phase contacting power. Since this gas-phase component of the contacting power should be more effective than the apparent liquid-phase component, an ejector scrubber might be expected to give higher collection efficiencies than a spray scrubber having nominally the same liquid-phase contacting power but no ejector effect. This phenomenon can account for part of the difference in performance between the ejector scrubbers and the SS1, SS2, and SS3 scrubbers.

The same conclusion should hold true even in cases in which the blower was operated in conjunction with the Configuration SS5 spray and spray-orifice scrubbers. Although there was a net gas pressure drop across the scrubber, part of the draft was supplied by the water jet, and some of the nominally liquid-phase contacting power was effectively gas-phase contacting power.

Presumably the droplet size of a spray should be a critical factor in particle collection, yet there was no indication that it had a major influence independent of the liquid-phase contacting power. It appears that, parallel to the case of contactors that draw their contacting power from the gas stream, the efficiency of spray contactors on a given aerosol depends almost entirely on the liquid-phase contacting power, with little influence of contactor design or geometry. Although the SS4 configuration appears to be a relatively distinct exception to this rule, this may be explainable as a case in which the actual liquid-phase contacting power is reduced by internal nozzle friction.

If it is generally true that the maximum attainable collection efficiency depends only on liquid-phase contacting power, with spray droplet size having no independent effect, then the same performance should probably be attained with spray nozzles actuated by other means than liquid pressure--for example, by mechanical spray generators or pneumatic or steam atomization. A pneumatic atomizer may add a substantial volume of gas to that entering the scrubber. Whether the added flow of gas in the gas-liquid contacting zone will have an appreciable effect on the aerosol collection is problematical.

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APPENDIX A

LITERATURE REVIEW*

The development of the "contacting power rule" is described in a series of four papers;[1-4] these papers also reviewed and correlated most of the available data up to 1963 that were given in sufficient detail to permit correlation. The general conclusion was that the performance of a particulate scrubber could be correlated by an equation of the form

$$N_t = \alpha P_T^{\gamma} \qquad (1)$$

where P_T is the total contacting power as defined in the Glossary and α and γ are empirical constants that are essentially characteristic of the aerosol only. Data from a variety of sources[2-4] confirmed the general form of the relationship and lent much support to the equivalence of different types of scrubbers in which the total contacting power was derived from the gas stream in the form of gas pressure drop. Walker[5] and Walker and Hall[6] made pilot plant and plant-scale tests of scrubbers and reached the same general conclusions.

Since the late 1950s the contacting power rule has become widely accepted among users and manufacturers of scrubbers. The physical demonstration of this acceptance is the widespread production and use of the variable-throat venturi or orifice scrubbers that are now produced, in one form or another, by all the major scrubber manufacturers and by some users as well. Much of the acceptance was based on general experience with pilot-plant or full-scale scrubbers operated on industrial dusts, fumes, or mists. The results of such tests have commonly been reported sketchily if at all.

There have been few attempts to carry out systematic comparative studies of different devices. More commonly, investigations have been concerned with a single device, sometimes with minor variations. The results of a number of such investigations have been reviewed in a previous report.[7] Discrepancies or outright contradictions among the reported results of different investigations have been common. In some of these instances, it has been obvious that the testing techniques have been defective. At least some of the claims of high scrubber efficiency on fine dusts with low power consumption have appeared because investigators made tests with redispersed dusts that were still highly flocculated, but assumed that the effective particle size and size distribution were the same as given by some method for measurement of ultimate particle size.

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*References for this appendix are collected at the end.

Becker et al.[8] reported the results of a test-stand comparison of about 14 commercial scrubbers of the low-, intermediate-, and high-energy types whose power consumption could be measured in terms of the gas pressure drop. Each was tested in its designed operating range. All the tests were made with a standardized slate dust, which was redispersed with a compressed air ejector. The measured penetrations of the different scrubbers fell in a reasonably narrow band when plotted as functions of the gas pressure drop.

A similar testing program was carried on by Bayer AG and reported at stages by Wicke[9] and Holter.[10] Tests were made with dusts redispersed with a compressed air ejector. However, most of the conclusions were evidently drawn from fractional efficiencies based on particle-size distributions determined by centrifugal sedimentation. Apparently, samples of the dust fed and of that penetrating the scrubber under test were analyzed by this technique. However, there is no reason to expect that the dust fed was actually dispersed to the ultimate particle size measured by the sedimentation method; hence, the absolute magnitudes of the data reported--at least--are questionable. Some of the data[9] make it obvious that the dust fed was partly flocculated. It is not apparent that even the effective particle size of the flocculated dust fed in the tests of different scrubbers was always the same. Depending on the scrubber design, a flocculated dust may be partly deflocculated in the scrubber itself before it can be effectively contacted by the water, and this may have significant effects on the performance.

The 28 different scrubbers tested by Bayer AG included some units with mechanically driven gas/liquid contactors. The performances of the different units were presented as functions of the power consumption (presumably of all forms of power used in any given scrubber). Substantial differences in performance were indicated for different devices, but it appears uncertain (as noted above) just what degree of significance these differences actually had.

Güntheroth[11] made an experimental study of the Pease-Anthony venturi scrubber and strongly asserted[11,12] that the collection efficiency was largely determined by gas velocity, liquid-to-gas ratio, and method of water injection, independent of gas pressure drop. Unfortunately, his data were presented only in part, and not in forms to permit ready extraction for correlation on the basis of gas pressure drop. Hence, the validity of Güntheroth's assertions is impossible to evaluate on the basis of his own published data. It can only be noted that his conclusions have not been confirmed by the preponderance of other work, and they have apparently not been repeated or applied since the original investigation.

Taheri and Haines[13] investigated different methods of water injection into a pilot-plant venturi scrubber, using a synthetic methylene blue test aerosol. They found a slight power saving (about 10%) with water feed through a weir rather than through spray nozzles or a continuous slot. The scatter in the data appear to indicate that the aerosol particle-size characteristics fluctuated considerably.

Taheri et al.[14,15] studied the operation of a small scrubber with orifice contactors and a butterfly-valve contactor. They used a synthetic methylene blue aerosol, and measured the inlet and outlet aerosols with four-stage cascade impactors. Collection efficiencies were measured for each of the three size fractions (small, medium, and large particles) into which the aerosol was classified by the cascade impactors. Unfortunately, Taheri et al. chose methods of plotting the data that tended to obscure the effects of the variables. In certain regions of operation, the efficiency at a given pressure drop was found to vary with water rate, orifice size, or the position of the butterfly valve. These independent effects of the variables other than pressure drop tended to disappear at higher water rates. It seems likely that the variations in behavior were associated primarily with low liquid-to-gas ratios.

With both gas/liquid contactors, the scrubbers gave lower collection efficiencies with the medium particles than with either the coarse or fine particles. Taheri et al. concluded[14] that the minimum efficiency (at a particle size of about 0.8 μm) was determined by the transition from diffusion-controlled to inertia-controlled particle collection, but the particle size seems unreasonably high for such an explanation.

Starting from Equation (1), Cooper[16] derived relationships that purportedly showed that if gas/liquid contacting is carried out in multiple stages instead of a single stage, the collection efficiency obtained should be greater or lower than that for the single stage, depending on the value of γ. However, his derivations required assumptions that are not applicable to any real system. Cooper illustrated his derivations with a convenient case in which all the contacting power took the form of gas pressure drop. He assumed two cases, one in which the values of α and γ are the same for the single-stage scrubber and for each stage of the multiple-stage scrubber, and another in which each stage of the multiple-stage scrubber has the same values of α and γ but these values are different from the α and γ values for the single-stage scrubber. He then determined that for the first case, the multiple-stage scrubber should give higher efficiency than the single-stage scrubber for $\gamma < 1$ and lower efficiency for $\gamma > 1$. For the second case, the relationship was more complex. Cooper also determined that the effect of the variation of γ should be a maximum if each of the multiple contact stages of a scrubber had the same pressure drop.

The essential deficiency in the derivations lies in the assumption of constant values of α and γ in a series of scrubber stages. This assumption is equivalent to a statement that each identical scrubber stage has the same efficiency, or value of N_t. The values of α and γ

are dependent on the character of the aerosol entering the scrubber whose performance is defined by Equation (1). (This is the case regardless of whether or not the values of α and γ are assumed also to be affected by the scrubber design.) For α and γ to remain constant from stage to stage, the aerosol must also remain constant, which can hold true only under one of the following conditions:

(1) The aerosol is precisely monodisperse.

(2) The aerosol is polydisperse but the efficiencies on each size of particle are such that the particle-size distribution remains precisely constant from stage to stage.

The first condition is, for all practical purposes, an intellectual abstraction. The chance that the second condition will occur is infinitesimal, and the situation would have no generality in any case. Thus, Cooper's hypothetical cases do not represent any real conditions that could be expected to exist.

In a real series scrubber, the aerosol particle size and size distribution will be altered during passage of the gas through each stage. Thus, each stage in succession will be presented with a "new" aerosol for which the α and γ values will be different. Whether the overall efficiency for any given multiple-stage scrubber will be different from that of a single-stage scrubber having the same pressure drop (or effective friction loss) will have to be determined experimentally. It cannot be assumed that different series contactors in general will necessarily give efficiencies consistently higher or lower than will be obtained with single-stage contactors.

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Appendix B

AEROSOL GENERATOR[*]

The main component of the aerosol generator was a modified Mist-O_2-Gen Model EN145 Ultrasonic Nebulizer. The commercial device consists of a ceramic piezoelectric crystal mounted in the bottom of a nebulizer chamber. The liquid to be atomized is placed in the chamber and is in direct contact with the crystal. A power source supplies radiofrequency energy at 1.4 MHz to the crystal, whose vibrations produce cavitation in the column of the liquid above the crystal. Fine droplets of the liquid ejected from the liquid column are carried out of the chamber with an air stream supplied for that purpose. The commercial use for the device is the preparation of therapeutic aerosols in a droplet size range suitable for inhalation therapy.[1,2]

The basic aerosol generation system was modified in an SRI-supported program in an attempt to stabilize the output and character of the aerosol over long periods of operation. The original plastic nebulizer chamber was replaced by a chamber consisting of a section of heavy-wall glass tubing of 7.6 cm i.d. held between two stainless steel flanges. The chamber was 26 cm high, and was designed so that the Mist-O_2-Gen transducer unit that contains the piezoelectric crystal could be attached directly to the bottom. The solution to be nebulized was supplied continuously to the chamber by gravity flow from an elevated reservoir. The liquid level in the chamber was maintained at 7.5 cm by means of a vented feed tube within the chamber.

Presaturated air entered the chamber tangentially, imposing a slight centrifugal field on the aerosol stream being carried out at the top of the chamber. The centrifugal field and a baffle at the exit of the chamber served to remove coarse spray droplets from the aerosol stream.

The ultrasonic transducer delivers about 50 watts of power in the atomization process. Much of this energy is dissipated as heat and is absorbed by the solution. Some of the heat is carried out of the nebulizer by the air stream, but the temperature of the solution tends to rise. Changes in room temperature can also affect the solution temperature. Temperature changes may affect the operation of the generator and the characteristics of the aerosol, directly or indirectly. A temperature control system was therefore incorporated into the aerosol generation system. The nebulizer chamber was insulated for protection against room temperature changes and air drafts. The solution in the nebulizer changer was maintained at a fixed temperature by circulation through a heat exchanger coil submerged in a constant-temperature bath. A small diaphragm pump was used to pump the solution from the bottom of the chamber, through the heat exchanger coil, and back into the nebulizer. The bath temperature was maintained at 30°C throughout the study of scrubber performance.

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[*] References for this appendix are collected at the end.

Since the size of a particle produced from a droplet after evaporation of the solvent depends on the concentration of the original solution, concentration of the solution by evaporation will result in an increase in particle size. If the air used to carry the aerosol out of the nebulizer were dry initially, it would also carry out some of the solvent as vapor, leaving the solution more concentrated. In the aerosol generator system, this problem was avoided by preliminary saturation of the air at the temperature of the solution. Compressed air was passed through a small ejector where solvent was drawn into the air stream and atomized. The mixture of air and solvent (air and water in the present study) was circulated through a stainless steel coil immersed in the same constant-temperature bath as was used to control the temperature of the solution in the nebulizer. The liquid water was then separated from the air in a small centrifugal separator and returned to the humidifier solvent reservoir, and the saturated air entered the nebulizer chamber. The ejector nozzle served as a critical-flow orifice for the air, and the air rate was regulated by setting the upstream air pressure.

It was found that variations in the voltage and wave form of the electric current supplied to the power source unit of the generator affected the quality of the energy that was in turn supplied to the piezoelectric crystal. Therefore, a harmonically compensated voltage regulator was inserted in the power supply line to the generator power source.

The nominal liquid nebulization rate was about 1 cm^3/min, but the actual rate varied from 0.5-1.5 cm^3/min. The aerosol output rates varied with the carrier air rate, but also varied for undetermined reasons that apparently were associated with the operation of the transducer itself. Fortunately, the variations in aerosol generation rate did not produce corresponding variations in the particle-size characteristics of the aerosols generated.

The variations in the particle size and/or particle-size distribution of the aerosol, as shown by the aerosol signatures, were evidently not correlated with generator temperature, generator power input, or aerosol generation rate. The variations did not, in fact, appear to be correlated with any observed influence. Neither did they appear to be completely random in their magnitudes. Instead, certain relatively discrete aerosol forms appeared with greater or lesser frequencies. In a total of 49 determinations made on Aerosol D, nine reasonably identifiable replicated variations of the aerosol appeared, with the number of replications of individual variant forms ranging from 2 to 17. Another variant form appeared only once.

The determination of replications was made by superimposing the graphs of the aerosol signature curves. The judgment of replication was based more on the coincidence of the complete curves than on the agreement of the total number of transfer units for the four-stage mini-scrubber. Curves that appeared to differ by no more than probable experimental error were considered to be replicates. A considerable number of exact replicates were encountered. The variant form of the aerosol that appeared with the greatest frequency (35%) is shown as the middle curve in Figure 18 of the report defined by the solid circular data symbols and broken line. This variant form and three other forms differing only moderately from it appeared with a combined frequency of 63%.

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GLOSSARY

Aerosol signature curve: The scrubber performance curve produced by a miniscrubber run on a given aerosol.

Actual conditions (gas): The actual temperature and pressure of a gas at the point of reference.

Collection efficiency: The fraction (η) or percentage (100η) of an aerosol entering a collection device that is removed from the gas stream by the device.

Contacting power: The power that is dissipated in fluid turbulence (and ultimately as heat) in the gas and liquid phases during gas/liquid contacting in a scrubber. It is commonly expressed in units of power per unit of volumetric gas flow rate:

$kW/(1000 m^3/hr)$ or $kWh/1000\ m^3$	Metric units
$hp/(1000\ ft^3/min)$	English units

Effective friction loss: The equivalent of contacting power, expressed in terms of equivalent gas pressure drop (due to friction loss only) across the gas/liquid contactor. In most cases, it is approximately equal to the actual gas pressure drop across a device that takes all its contacting power from the gas stream. It is commonly expressed in the same units as gas pressure drop:

cm WC (centimeters of water column)	Metric units

Liquid-to-gas ratio: The ratio of the volumes of liquid and gas brought into contact in a gas/liquid contactor. It may be expressed on the basis of the gas volume either at actual or at standard conditions:

$liters/m^3$ (liters of water per actual cubic meter of gas)	Metric units
$liters/std\ m^3$ (liters of water per standard cubic meter of gas)	

Scrubber performance curve: A correlation curve expressing the functional relationship between the number of transfer units and the contacting power (or effective friction loss). This is most conveniently presented on a log-log plot.

Scrubber pressure drop: The total drop in gas pressure across a gas scrubber, whether due to friction loss or to kinetic energy changes. It is commonly expressed as the equivalent fluid head loss:

cm WC (centimeters of water column)	Metric units
inches WC (inches of water column)	English units

Standard conditions (gas): The selected reference temperature and pressure for specification of gas volumes. In this report, the standard conditions are 25°C (77°F) and 1 atm pressure.

Transfer unit: Defined by the relationship

$$N_t = \ln\,[1/(1 - \eta)]$$

where N_t = number of transfer units and η = fractional collection efficiency.

CONVERSION FACTORS

Gas Flow

$1\ \mathrm{m^3/hr} = 0.58857\ \mathrm{ft^3/min}$

$1\ \mathrm{m^3/min} = 35.316\ \mathrm{ft^3/min}$

$1\ \mathrm{liter/min} = 0.035316\ \mathrm{ft^3/min}$

Gas Velocity

1 m/sec = 3.2808 ft/sec

Liquid Flow

1 liter/min = 0.26418 gal/min

1 liter/hr = 0.0044030 gal/min

$1\ \mathrm{m^3/hr} = 4.4029\ \mathrm{gal/min}$

Liquid-to-Gas Ratio

$1\ \mathrm{liter/m^3} = 7.4808\ \mathrm{gal/1000\ ft^3}$

Pressure

$1\ \mathrm{atm} = 1.0133 \times 10^5\ \mathrm{N/m^2}$ (pascals)

1 cm WC = 0.39370 inch WC

$1\ \mathrm{cm\ WC} = 97.968\ \mathrm{N/m^2}$ (60°F)

Contacting Power

$1\ \mathrm{kWh/1000\ m^3} = 2.2784\ \mathrm{hp/(1000\ ft^3/min)}$

Effective Friction Loss

1 cm WC = 0.39370 inch WC

1 cm WC = 0.02724 kWh/1000 m^3

1 inch WC = 0.1575 hp/(1000 ft^3/min)

Aerosol Concentration

1 $mg/m^3 = 4.3697 \times 10^{-4}$ grain/ft^3